



REVIEW DRAFT

**CONTROL AND MITIGATION OF DRINKING WATER
LOSSES IN DISTRIBUTION SYSTEMS**



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Acronyms and Abbreviations

AM	Asset Management	NSF	NSF International (Formerly National Sanitation Foundation)
AMR	Automatic Meter Reading	O&M	Operation and Maintenance
ANSI	American National Standards Institute	PCCP	Prestressed Concrete Cylinder Pipe
ASCE	American Society of Civil Engineers	PRV	Pressure Reducing Valve
ASDWA	Association of State Drinking Water Administrators	PVC	Polyvinyl Chloride
ASTM	American Society for Testing Materials	PWS	Public Water System
AWWA	American Water Works Association	SCADA	Supervisory Control and Data Acquisition
AwwaRF ..	American Water Works Association Research Foundation	TILDE	Tools for Integrated Leak Detection
BABE	Breaks and Burst Estimation	WARN	Water & Wastewater Agency Response Network
CADD	Computer-Aided Design and Drafting	UARL	Unavoidable Annual Real Losses
CARL	Current Annual Volume of Real Losses	UFR	Unmeasured Flow Reducer
CUPSS	Check-Up Program for Small Systems	US	United States
DMA	District Metered Area		
DWSRF	Drinking Water State Revolving Fund		
ELL	Economic Level of Leakage		
EPA	United States Environmental Protection Agency		
FAVAD	Fixed and Variable Discharge Paths		
gpm	Gallons Per Minute		
GRP	Ground Penetrating Radar		
IWA	International Water Association		
ICCP	Impressed Current Cathodic Protection		
ILI	Infrastructure Leak Index		
ISO	International Standards Organization		
MassDEP...	Massachusetts Department of Environmental Protection		
NRWA	National Rural Water Association		
NTNCWS ..	Non-Transient Non-Community Water System		

Executive Summary

Maintaining system infrastructure to deliver clean and safe drinking water to customers is often a significant challenge for the operators of public water systems (PWSs). Much of the estimated 880,000 miles of drinking water infrastructure in the United States has been in service for decades and can be a significant source of water loss. In addition to physical loss of water from the distribution system, water can be “lost” through unauthorized consumption (theft), administrative errors, data handling errors, and metering inaccuracies or failure. Water is a commodity that is produced by a PWS; therefore, lost or unaccounted-for water can be equated to lost or unaccounted-for revenue. A water loss control program can help to locate and reduce these water losses and thus maintain or increase revenue.

A PWS must balance use of its resources to address the financial and personnel demands of economic restrictions, water availability, population and climate changes, regulatory requirements, operational costs, and public and environmental stewardship. A water loss control program can help identify and reduce actual water losses along with apparent losses resulting from metering, billing or accounting errors. Water loss control programs can potentially defer, reduce, or eliminate the need for a facility to expend resources on costly repairs, upgrades, or expansions. A water loss control program will also protect public health through reduction in potential entry points of disease-causing pathogens.

A water loss control program is an iterative process that must be flexible and customizable to the specific needs of a PWS. There are three major components of an effective water loss control program that must be repeated on a periodic basis to continually evaluate and improve the performance of a PWS. These three components are the 1) Water Audit, 2) Intervention, and 3) Evaluation.

Conducting a water audit is a critical first step in developing a water loss control program. A water audit quantifies the amount of water that is being lost. Most states have regulatory policies that set acceptable losses from PWS distribution systems at a maximum of between 10 and 15 percent of the water produced by the PWS. This percentage of unaccounted water provides estimated losses and does not adequately quantify how or why this water is categorized as “unaccounted-for”. Lack of standardized terminology has historically added to difficulties in comparing water losses from different PWSs. The International Water Association (IWA) and the American Water Works Association (AWWA) have developed standard methods and terminology to perform water audits and to assist water utilities in tracking their distribution system losses. The AWWA/IWA water audit methodology is based on the water balance table, which specifies different types of water consumption and losses. Through the water audit,

options will become apparent regarding how to proceed with further identifying where losses are occurring or where efforts to control or eliminate the losses should be concentrated.

The Intervention process begins to address the findings of the water audit and can include a variety of actions such as gathering of further information, implementing metering programs, adding or changing metering, and detecting and repairing leaks. The selected intervention option should provide the highest potential benefit value for the resources available that will help to alleviate a flaw or deficiency in the distribution system.

The evaluation portion of the program consists of assessing the success of the audit and intervention actions. The evaluation of an intervention action can be as simple as answering a yes or no question – *Was the leak located and repaired?* – but more often provides detailed quantification of the implemented action through the use of performance indicators – *The pipe replacement resulted in a reduction of water losses of 1,000 gallons per customer per year.*

Performance indicators numerically evaluate different aspects of the distribution system and need to be consistent, repeatable and presented in meaningful standardized units. A performance indicator (or collection of several) can be used to establish a benchmark. A benchmark allows a PWS to evaluate its performance over a period of time by repeating the performance indicating tests and comparing them with previous results. Performance indicators and benchmarks also allow comparisons between public water providers.

Accurate metering is crucial in a water loss prevention program. Metering establishes production and customer use volumes as well as provides historic demand and consumption data that is useful not only for auditing but for planning future needs. There is no single type of meter that will accurately measure flow for all applications but there are a variety of meters, that have been developed using different operating principles, designed to perform within required tolerances under different circumstances. The cost of meters typically ranges from a few hundred dollars to thousands of dollars per meter depending on size, complexity, and operating conditions. A PWS must select the meters they use carefully according to intended use, flow rates, and the environment where it will be installed. How the meters will be read is also a decision that a PWS has to decide when considering metering programs. Meters can be read manually but most PWSs are moving toward a variety of different Automatic Meter Reading (AMR) systems that reduce reading errors and allow labor to be reduced or reallocated.

While it is possible to spot losses through billing data discrepancies or abrupt changes in amounts of water that have been historically used, it is typically necessary to physically pinpoint the leak in the field. The location of a leak is not always obvious unless it is large. An array of techniques and equipment are available to assess leakage from distribution lines within a

geographic area or pinpoint a leak within a suspected segment of pipe. Flow monitoring of a District Meter Area (DMA) or step-testing techniques are often used to determine leakage within an area that can be isolated and may encompass 1,500 to 2,000 service connections. These techniques monitor flow to specific areas and compare water flowing into the area with known or estimated night usage to determine losses in the DMA or along a branch water line.

There are several different types of leak detection equipment that use different operating principles. Acoustic equipment detects a leak through noise made by water as it leaks from the pipe. Electromagnetic field detection is used on pre-stressed concrete pipe and locates defective reinforcing steel in the pipe. Thermal detection devices look for the temperature differences in the surrounding ground caused by saturation due to the leaked water. Chemical detection relies on locating substances added to the treated water such as chlorine or fluoride that do not occur naturally. A trace gas may also be introduced into dewatered lines. If there is a leak, a special instrument can detect it at the surface. The different styles of leak detection equipment require varying levels of skill and experience to operate with accuracy. Capital costs for typical leak detection equipment range from less than one hundred to several thousand dollars depending on its complexity.

Once a leak is located it can be repaired or replaced. Some repair techniques include wrapping, using repair clamps, or sliplining. Replacement can be done by installing new pipe in an excavated trench or by use of a trenchless method such as pipe bursting where a new pipe of the same size or larger is pulled through the existing pipe with special equipment. Micro tunneling or and hydraulic jacking are other trenchless techniques where pipe is either pushed or pulled underground without the necessity of large amounts of excavation.

Operations and maintenance (O&M) procedures and standards should also be a part of any water loss prevention program. Along with ensuring proper design, and installation of new distribution components, maintenance and operation measures such as system flushing, valve exercising, meter assessment testing and replacement programs, system modeling, and pressure management all contribute to improved efficiency, reduction in water losses, and often cost savings.

Developing a complete water loss prevention program requires careful consideration of the water loss reduction goals a PWS wishes to achieve. The program should be customized for the unique features of the PWS and be flexible enough to update periodically as the PWS conducts future audits. Those assembling a water loss prevention program should also remember there is help available from the EPA, other PWSs, state drinking water primacy agencies, and other drinking water trade and conservation organizations.

1 WATER LOSS CONTROL PROGRAMS FOR PUBLIC WATER SYSTEMS

1.1 INTRODUCTION

Safe drinking water is a necessity for life. Every day billions of gallons of this precious commodity are delivered to millions of people across the United States (US). Thousands of independent water utilities around the nation are dedicated to producing, treating, and delivering safe water to the public. Significant resources are required to install, operate, and maintain the infrastructure of a public water system (PWS). PWSs are facing more obstacles and challenges today than they have in the past with more resource and funding constraints. The infrastructure of many of the drinking water systems in the US were built decades ago and are currently in need of attention. PWSs are not only expected to produce safe drinking water at a low cost but must also address current growing concerns such as limited water availability, increasing water demands, climate change, increasing regulatory requirements, and limited resources and funding.

The deterioration of the infrastructure of these drinking water systems has become a critical issue. There are approximately 880,000 miles of drinking water infrastructure in the US. In the American Society of Civil Engineers' (ASCE) 2005 *Report Card for America's Infrastructure* it was estimated that there will be at least an \$11-billion annual shortfall over the next 20 years in funds necessary to replace aging facilities and meet existing and future drinking water regulations. As the integrity of our aging infrastructure decreases, the loss of finished water in the distribution system increases. The loss of integrity in the distribution system is evident by the increasing amounts of reported breaches in distribution systems. The loss of finished water in the distribution system results in direct loss of revenue for the PWSs. The American Water Works Association (AWWA) estimated in the *Distribution System Inventory, Integrity and Water Quality* publication that there are close to 237,600 breaks per year in the United States leading to approximately \$2.8 billion lost in yearly revenue.

Water loss from a utility's distribution system is a growing management problem that is not only confined to lost revenue. Water losses in the distribution system require more water to be treated, which requires additional energy and chemical usage, resulting in wasted resources and lost revenues. With growing concerns about shrinking budgets, PWSs must look at how they can optimize their production and revenue. Water lost in the distribution system equals revenue lost. For these reasons more and more PWSs across the country are implementing water loss control programs. Not only can a well implemented water loss control program reduce revenue loss but it can also protect public health by eliminating the threat of sanitary defects that may allow microbial contamination in finished water.

This guidance has been prepared for water management administrators, local government officials, system operators, and others who have an interest in developing programs to reduce losses from their drinking water distribution systems. The success of a water loss control program depends on the ability to tailor the program to the individual PWS. This guidance provides information on flexible tools and techniques that may help the PWS meet their water loss prevention needs.

1.2 GROWING CONCERNS PUBLIC WATER SYSTEMS FACE AND HOW A WATER LOSS CONTROL PROGRAM CAN HELP

A public drinking water system must provide enough water to meet demand at a reasonable cost while maintaining quality standards to protect public health. A PWS and its water management administrators must balance these goals at the same time they face growing concerns such as:

- Water availability
- Economic restrictions
- Population growth
- Climate change and drought
- Operational and maintenance costs
- Regulatory requirements
- Public service responsibility
- Social pressures and environmental stewardship

Many of these issues are inter-related. A water loss control program can help to address each of these issues.

Water Availability

The complexity of PWSs varies with a community's size, composition, and location. All systems depend on quality and abundant water sources to meet increasing water demands. A PWS's source may be ground water, surface water, ground water under the influence of surface water, purchasing finished water from another PWS or a combination of these sources. Each of these options requires resources and funds to locate, develop, treat, and maintain the source. When insufficient availability becomes an issue, a PWS has the option to find and develop another source or buy additional water from another PWS. However, finding a new reliable and adequate quality source may not always be easy or an option. A third option available to the PWS is to take a look at their process and operation and determine if there is any way to save water. This is when developing and implementing a water loss control program at the PWS becomes essential. Through a water loss control program, water that was previously lost can now be sold to the consumers, increasing revenue, meeting water demands and reducing the need

for other sources. Such a program may be able to defer development of new sources and reduce or eliminate the need to supplement supply from another PWS. The water loss control program is often the most economical solution.

Economic and Population Growth

Population growth can put an additional strain on a water system. Economic, manufacturing, and industrial growth in a community can also affect the ability of a water system to provide sufficient water. Some industries rely heavily on water such as food processing and beverage companies. These water demand increases must be met either by locating other sources, increasing the capacity of the existing water treatment facility, or investing in new capital improvement projects. A water loss control program can help find water that was previously lost in the system and potentially defer, reduce, or eliminate the need for more expensive alternatives.

Climate Change and Drought

Droughts are naturally occurring phenomena. Periods of drought can contribute to increased water demand and add strain to the PWSs source water supply. Drought effects can be especially critical in the more arid Southern and Western regions of the United States.

Governmental agencies track drought data to predict water and resource needs. Drought maps like the one in Figure 1-1 for August of 2008 can be found at <http://drought.unl.edu/dm>. A water loss control program can help lessen the severity of the effects of drought and climate change on PWSs through retention of more water in their distribution system. This not only has the effect of retaining more water for the customers, but can lessen the amount withdrawn from the source.

U.S. Drought Monitor

August 5, 2008
Valid 8 a.m. EDT

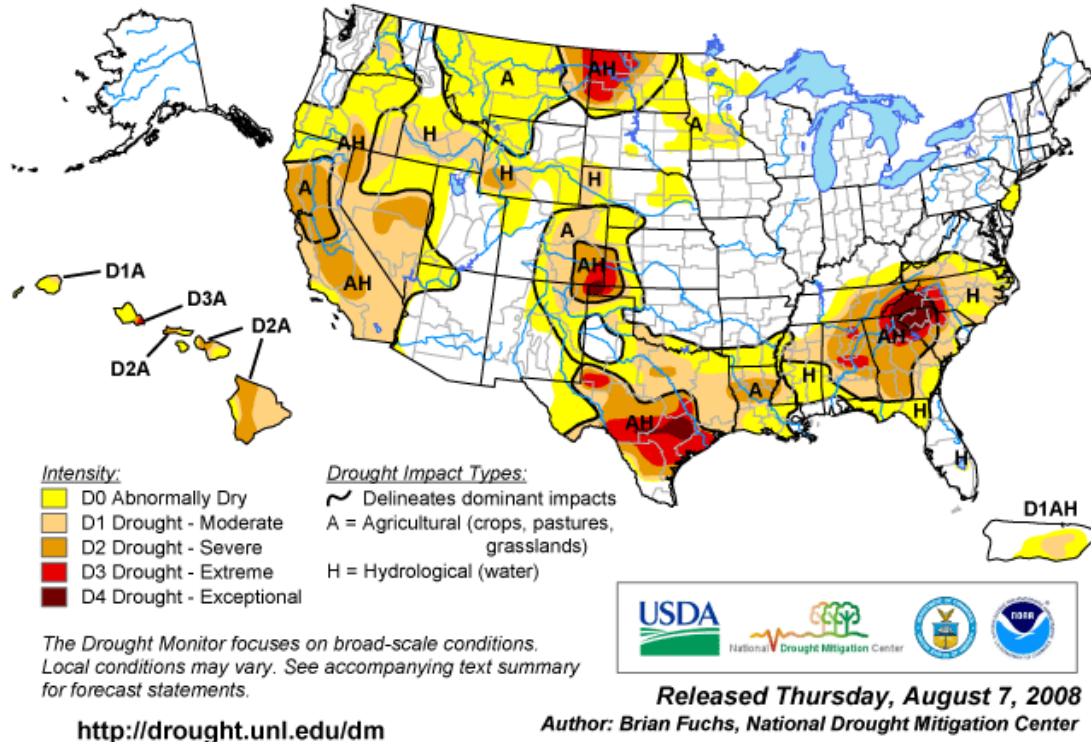


Figure 1-1. Drought Conditions During August 2008.

Source: National Drought Mitigation Center, August 2008

Operational and Maintenance Costs

Water loss control and prevention programs can also benefit the bottom line of a PWS. Reduced water losses in the distribution system can translate to:

- Less electricity required to treat and pump the water,
- Potential reduction in the feed rates of treatment chemicals, and
- Potential reduction in disinfectant dose.

It can also mean deferred treatment facility upgrades. Savings may also be realized through reduced equipment maintenance and replacement. Along with fewer breaks and leaks to be repaired, the service life of distribution piping may be extended through pressure management and surge suppression schemes. Review of metering accuracy and other metering programs can recover lost revenues. Metering and pressure management will be discussed further in the following chapters.

Regulatory Requirements

Currently, there are no national requirements for auditing and reporting water loss from PWSs, but some states have taken it upon themselves to begin regulating and assessing water loss from systems in their jurisdictions. Texas, for example, became a leader in the push to control water loss with the passing of House Bill 3338, which required all Public Water Utilities to conduct water audits for 2005 operations and every five years thereafter. The water audit report addresses four main points of water loss: distribution line loss, meter inaccuracies, accounting practices, and service theft. Many other states have existing rules regarding losses from PWSs and are continuing to tighten and enforce these requirements. A water loss control program can make complying with these existing and future regulations easier.

Public Service Responsibilities

A water loss control program can contribute significantly to a PWSs responsibility to provide its customers with safe water. Through a water loss control program, potential points of entry for microbial and other contaminants are reduced, increasing public health protection. Some facets of the program can reduce main breaks and the collateral damage associated with locating and repairing these breaks. For example, a water audit may identify sources of water loss in the distribution system. By addressing water leaks proactively, the PWS can prevent interruptions in service and reduce the cost of repair. Other potential benefits to the customers include: deferred rate increases, better distribution system reliability, and improved ability for the distribution system to meet the higher water pressure and flows required for fire fighting. Combined, these benefits ultimately increase customer satisfaction and reputation of the PWS.

Social Responsibility and Conservation

In addition to the benefits to the PWS and its customers, a water loss control program can have further overarching benefits. Increasing social, government and public pressures have changed the way society conserves water resources to ensure future sustainability. Not only will a water loss control program help conserve water, but it can directly impact the amount of electricity and treatment chemicals used. It may lead to conservation of materials and fuels used in maintenance and repairs. Combined, the reduction in use of these resources can help reduce greenhouse emissions.

1.3 WATER LOSS CONTROL PROGRAM COMPONENTS

A water loss control program must be flexible and tailored to the specific needs and characteristics of a PWS. There are three major components to an effective program:

1. The Water Audit
2. Intervention

3. Evaluation

Each of these major components consists of additional steps and options.

The *Water Audit* is an assessment of the distribution system and uses accounting principles to determine how much water is being lost and where. Through the water audit, options will become apparent as to how to proceed with further identifying where losses are occurring or where efforts to control or eliminate the losses should be concentrated. These options should be compared and evaluated not only economically but with consideration of all other issues and concerns the PWS faces. Typical steps in an audit include:

- Gathering information,
- Determining flows into and out of the distribution system based on estimates or metering,
- Establishing performance indicators (e.g., what parameters will be measured and how),
- Assessing where water losses appear to be occurring based on available metering and estimates,
- Analyzing data gaps (e.g., determining if more information is necessary to make comparisons and an informed decision),
- Considering options and making economic and benefit comparisons of potential actions, and
- Selecting the appropriate interventions.

The *Intervention* process puts the options selected into action. More than one action may be selected as beneficial to a PWS and the public. For example, the water management administrator may decide that the PWS has three high priority items including adding additional metering in one neighborhood, precisely locating and repairing a leak in a specific section of main, and replacing a one-mile section of pipe. Selecting the order of these actions should be based on budget constraints, public benefit, and priority of other scheduled capital improvements. Intervention can include:

- Gathering further information, if necessary,
- Metering assessment, testing, or a metering replacement program,
- Detecting and locating leaks,
- Repairing or replacing pipe,
- Operation and maintenance programs and changes,
- Administrative processes or policy changes, and

- No further action is necessary.

The *Evaluation* portion of the program consists of assessing the success of the audit and intervention actions. The evaluation will answer questions such as:

- Were the goals of the intervention met? If not, why not?
- Where do we need more information?
- How often should we repeat the Audit, Intervention and Evaluation process?
- Is there another performance indicator we should consider?
- How did we compare to the last Audit, Intervention and Evaluation process?
- How can we improve performance?

A major portion of evaluation is benchmarking. The audit establishes performance indicators, which serve as benchmarks. The intervention action should improve performance in some way. Evaluation is necessary to ensure that whatever the intervention was, it succeeded in its goal. If the goal of the intervention was not met, the evaluation process seeks to determine why and what can be done about it.

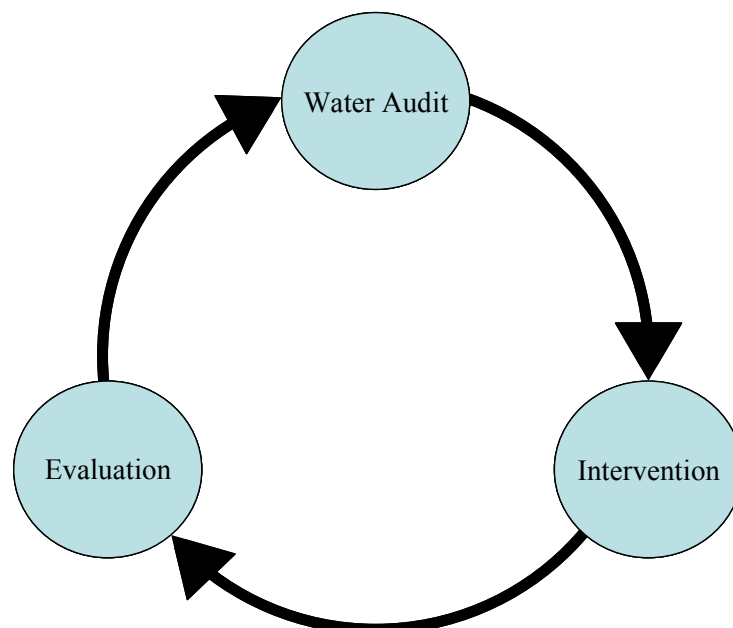


Figure 1-2. Water Loss Control Program Components.
A water loss control program as a continuous process.

2 WATER LOSS TERMS AND CONCEPTS

2.1 INTRODUCTION

There is no current comprehensive national regulatory policy that limits the amount of water loss from a public water supply's distribution system. Most states, however, do have policies and regulations that address excessive distribution system water losses. The policies vary among states but most set limits that fall within the range of 10% to 15% as the maximum acceptable value for the amount of water that is lost or "unaccounted-for."

Neither the term "unaccounted-for-water" nor the use of percentages as measures of water loss is sufficient to completely describe the nature and extent of distribution system water loss.

Unaccounted-for-water is a term that has been historically used in the United States to quantify water loss from distribution systems. Unaccounted-for-water, expressed as a percentage, is calculated as the amount of water produced by the PWS minus the metered customer use divided by the amount of water produced multiplied by 100, or,

$$\text{Unaccounted-for-Water \%} = \frac{(\text{Water Produced by PWS} - \text{Metered Water Used})}{\text{Water Produced by PWS}} \times 100$$

Although this percentage provides a rough idea of how much water is unaccounted for, it does not help answer questions such as is the water really being lost? If so where? Is water that is used for firefighting or by the city for street cleaning really unaccounted for? What about inaccurate meters, theft or billing errors? These situations all can contribute to unaccounted water but do not necessarily mean that there is excessive leakage in the distribution system. Determining how much water is being lost and where losses are occurring in a distribution system can be a difficult task. Without consistent and accurate measurement, water losses cannot be reliably and consistently managed. The confusion over inconsistent terms and calculations has led to the development of better tools and methods to track water losses from distribution systems.

The International Water Association (IWA) and the American Water Works Association (AWWA) began to finalize standard methods to assist water utilities in tracking their distribution system losses in the last several years. These methods are the foundation of water auditing and conservation strategies that are now being used successfully worldwide. In order to understand how to apply the AWWA/IWA methodology, several concepts and terms must be defined and explained. The AWWA/IWA Water Balance Table (Figure 2-1) is the foundation of the methodology and defines the terms used in water auditing. The water audit determines the type and quantity of water loss. Performance indicators can then be calculated to measure the level and volume of water losses in the PWS. These performance indicators then serve as benchmarks

to gauge improvement during the next scheduled audit. Performance indicators and benchmarks are discussed in more detail in Section 2.4.

2.2 THE WATER BALANCE

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption	Revenue Water
			Billed Un-metered Consumption	
	Water Losses	Unbilled Authorized Consumption	Unbilled Metered Consumption	Non Revenue Water (NRW)
			Unbilled Un-metered Consumption	
		Apparent Losses (Commercial Losses)	Unauthorized Consumption	
		Real Losses (Physical losses)	Customer Meter Inaccuracies and Data Handling Errors	
			Leakage in Transmission and Distribution Mains	
			Storage Leaks and Overflows from Water Storage Tanks	
			Service Connections Leaks up to the Meter	

Figure 2-1. The AWWA/IWA Water Balance Table

Standardized terminology and definitions are crucial to consistent measurement. These standards are needed to accurately track performance and improvements. In the AWWA/IWA methodology, all water that enters and leaves the distribution system can be classified as belonging to one of the categories in the water balance table shown in Figure 2-1; each of these terms is defined below. The table is balanced because it accounts for all of the water in the distribution system and the sum of any of the columns should also total the *System Input Volume*.

System Input Volume is defined as the amount of water that is produced and added to a distribution system by a PWS. It also includes water that may have been purchased from another water supplier to supplement the needs of the PWS.

Authorized Consumption is water that is used by known customers of the PWS. Authorized consumption is the sum of billed authorized consumption and unbilled authorized consumption and is a known quantity.

Billed Metered Consumption is an authorized consumption that is directly measured. It is the quantity of water that is metered and generates revenues through the periodic billing of the consumer.

Billed Un-metered Consumption is an authorized consumption that is based on an estimate or flat fee. This billing method is used for customers that do not have meters. Estimated use is

often based on historical or average use data. The fee may vary for different types of customers such as residential or industrial.

Unbilled Authorized Consumption consists of known uses, condoned by the utility, for which no revenue is received. Unbilled authorized consumption can be either **metered** or **un-metered**. Unbilled authorized consumption is shown in yellow in Figure 2-1. Some examples might include filling city street cleaner trucks or a city swimming pool, flushing water lines or sewers, or water used by the fire department. All are legitimate water uses, with the full cognizance of the utility.

Unbilled Metered Consumption is that quantity of water that does not generate revenues but which is accounted and not lost from the system. Water used in the treatment process or water provided without charges are examples of these quantities.

Revenue Water is water that is consumed and for which the utility receives payment. Revenue water consumption volume is measured or estimated. Revenue water includes metered and un-metered billed authorized consumption. Revenue water is shown in green in Figure 2-1.

Non-Revenue Water (NRW) is water that is not billed and no payment is received. It can be either authorized, unauthorized or result from a water loss. Authorized NRW consists of unbilled metered consumption and unbilled un-metered consumption.

Unbilled Un-metered Consumption is the quantity of water that is authorized for use by the PWS but is not directly measured and creates no revenues. Water main flushing and firefighting are often examples of this category.

Unbilled Metered Consumption is directly measured water use for which there is no charge. This category can include water use at city government offices, street cleaning or city park irrigation.

Some PWSs either meter or estimate use by the city or public services such as fire departments even though no fee is charged. These systems will have an advantage when preparing a water audit since this information will be required to complete the water balance.

Unauthorized Consumption is that quantity of water which is removed from the system without authorization and presumably without the PWS's knowledge. Unauthorized consumption includes theft by illegal meter by-passes, vandalism or un-metered hydrant use for construction or recreation. This water quantity is very difficult to estimate but must be accounted and is amenable to reduction through administrative action. Figure 2-2 shows a fire hydrant with a garden hose attached as an illustrative example of an un-metered and possibly unauthorized connection. Unauthorized consumption as in this example can also be a potential source of contamination because there is no backflow prevention device in use.



Figure 2-2. Hydrant With Un-metered and Possibly Unauthorized Use

The lower part of the Water Balance Table consists of **Water Losses**. Water losses are categorized as either real or apparent. **Real Losses**, also referred to as physical losses, are actual losses of water from the system. When performing financial calculations related to real losses, the water is priced at the cost of production rate since it is not available for a consumer to use and costs only what it takes to produce. Correcting real losses will result in lower operating cost through reduced production requirements and reduced water process chemical and electrical use.

Real Losses are the physical leaks shown in grey in Figure 2-1 and consist of leakage from transmission and distribution mains, leakage and overflows from the utilities storage tanks and leakage from service connections up to and including the meter. Preventing or repairing real losses usually requires an investment in PWS infrastructure. Infrastructure investment can reduce losses such as:

- **Distribution and transmission main leaks**, which represent the quantity of water that is lost from the system, generates no revenue, can severely damage system reliability if not corrected and may result in water quality problems.
- **Storage leaks and overflows from water storage tanks**, which consist of the quantity of water that is lost from the storage facilities within the system. Depending on the climate and storage configuration, these losses can also be due to surface evaporation.
- **Service connection leaks**, which consist of the quantity of water that is lost from leaks from the main to the customer's point of use. Even though a leak after a customer's meter can generate revenues for the PWS and is often the responsibility of the customer, it is wasteful and can strain customer and PWS relations. Service connection leaks represent real losses from the system and are frequently easy to detect. In the AWWA/IWA water audit methodology only service connection leaks up to the meter are included.

Apparent losses, also referred to as commercial losses, occur when water that should be included as revenue generating water appears as a loss due to theft or calculation error. Apparent losses consist of unauthorized consumption, metering calibration errors and data handling errors. Apparent losses are shown in orange in Figure 2-1.

Meter calibration error and data error losses can be thought of as accounting losses. This quantity of water is not lost from the system and generates no revenues but if not included in loss calculations can produce misleading water loss estimates. These errors arise from service meter calibration errors, meter reading errors, data handling and billing errors and billing period variances. These quantities may be reduced through administrative action.

When performing financial calculations related to apparent losses, the water is priced at the retail rate since it should have been charged at that rate. Recovering apparent losses will not reduce physical system leakage but it will recover lost revenue. Calibrating or replacing old meters or enforcing water theft policies can substantially reduce apparent losses.

Water Balance terms help classify and standardize the methods used in the water audit. The water audit is the starting point for the utility to understand its water loss. The audit is a methodical approach to account for all water that is placed into the distribution system and accounts for its ultimate disposition.

2.3 THE WATER AUDIT

The water audit is the critical first step in the establishment of an effective water loss management program. With the successful completion of a system water audit, the PWS will have gained a quantified understanding of the integrity of the distribution system and begin to formulate an economically sound plan to address losses. Water loss in a public water system can be a major operational issue. Non-revenue generating water can significantly affect the financial stability of the PWS. Finding and repairing water loss sites can carry its own substantial costs. The economic trade-offs between value of lost water given it generates no revenue and the investment to reduce this loss requires careful planning and economic judgment. The PWS needs to clearly understand the type of loss as well as its magnitude. Water resource, financial and operational consequences must be weighed when considering whether to fix the source of the leak. This decision is unique to every system.

There are several published water auditing software systems available for free or at a low cost. Several can be downloaded from internet Web sites. Care should be taken in selecting and applying water loss auditing software since many of these tools are based on European models and use metric units. AWWA provides free audit software that can be downloaded from: <http://www.awwa.org/Resources/WaterLossControl.cfm?ItemNumber=48511&navItemNumber>

=48158. A blank water audit worksheet is included in The Texas Water Development Boards' *Water Loss Manual* (2005). The manual along with the form can be downloaded from: http://www.twdb.state.tx.us/assistance/conservation/Municipal/Water_Audit/Leak_Detection/WaterLossManual_2005.pdf. The Massachusetts Department of Environmental Protection (MassDEP) also provides Water Audit Forms and worksheets at its Web site: <http://www.mass.gov/dep/water/approvals/wmgforms.htm#audit>. Blank Texas Water Development Board Water Audit Worksheets and Mass DEP forms are included in Appendix C.

A summary of steps to perform an initial water audit is as follows.

1. Determine the amount of water added to the distribution system, adjusted to correct for metering errors.
2. Determine authorized consumption (billed + unbilled).
3. Calculate water losses (water losses = system input – authorized consumption)
 - a. Estimate apparent losses (theft + meter error + billing errors and adjustments)
 - b. Calculate real losses (real losses = water losses – apparent losses).

These steps are an example of a **top down audit**, which starts at the “top” with existing information and records. It may also be known as a desktop audit or paper audit since no additional field work is required. Distribution systems are dynamic. The audit process and water balance has to be periodically performed to be meaningful to a utility’s water loss management program.

After performing an initial top down audit it may become evident that some of the numbers are rough estimates and inspire little confidence in their accuracy. The next action in the audit process is to refine and hone the quantities that may have been initially estimated and begin reducing non-revenue water losses. A **bottom up audit** is often implemented after several top down audits have been completed and can help find the leaks that were not revealed by the top down audit. A bottom up audit will help with finding real losses and begins by looking at components or discrete areas in the distribution system. A bottom up audit assesses and verifies the accuracy of the water loss data associated with individual components of the distribution system. Bottom up audits are more costly since they are more labor and staff intensive. The top down audit can help to identify areas where bottom up audit efforts should be concentrated.

Discrete metered areas (DMA) and night flow analysis are two major tools used in bottom up audits. A DMA is a specific area or section of pipe that can be isolated by closing valves so inputs and outputs can be monitored. The water flowing into the DMA is metered and compared with metered customer use. The difference is the water loss for the DMA. DMA analysis is usually done at night when water use is at a minimum. This **night flow analysis** minimizes

errors in the loss calculations by reducing potential customer meter error and by reducing pressure and use variations.

By standardizing the terminology utility operators can begin to accurately track the performance of their distribution system and use the water balance and water audits tools to help make sound financial decisions regarding the operation of their system.

2.4 PERFORMANCE INDICATORS AND BENCHMARKS

Periodically repeating the water audit allows a PWS to monitor its water loss performance over time or compare itself to other PWSs. This is called **benchmarking**. Benchmarking uses a collection of **performance indicators** to numerically evaluate different aspects of the distribution system. Performance indicators need to be consistent, repeatable and presented in meaningful standardized units. Examples of performance indicators include: breaks per mile of distribution main per year, cubic feet of water lost per service connection, gallons lost per mile of distribution main, gallons lost per customer, real losses in gallons per year and dollars of apparent losses per year.

PWSs may use benchmarking to record the values of one or more performance indicators. This data is then used to compare previously recorded values evaluated with the same units.

Benchmarking can be done at any increment of time: daily, monthly, yearly or every few years.

By benchmarking, a system can:

- evaluate its performance;
- locate areas where improvement is necessary;
- compare itself to other water systems;
- evaluate financial options;
- gauge itself competitively; and
- provide data for reports to the public, regulators and ultimate water users.

Although reductions of water theft and meter validation and replacement programs have their physical aspects, correction of apparent losses is largely an administrative effort. There is no physical defect in the distribution system that is allowing water to escape. This is not the case with real losses.

The AWWA/IWA audit methodology relies heavily on three performance indicators to help characterize real losses from distribution systems. These performance indicators are the Current Annual Volume of Real Losses (CARL), the Unavoidable Annual Real Losses (UARL) and the Infrastructure Leak Index (ILI).

The **Current Annual Volume of Real Losses (CARL)** is the volume of water that is lost from the system due to leaks in the transmission and distribution systems, losses at the utility's storage tanks and leaks in the service lines from the main to the point of customer usage. The CARL is given in gallons/day averaged over a one-year period. This total volume is largely straightforward and easily computed by most utilities. It should be recognized that this volume contains water losses that can be identified, located and repaired as well as those unavoidable leaks that every system contains.

$$\text{CARL (gallons/day)} = \text{Transmission Losses} + \text{Distribution Losses} + \text{Storage Losses} + \text{Service Line losses} \quad (\text{Eq. 2-1})$$

The **Unavoidable Annual Real Losses (UARL)** is a subset of a system's CARL leaks that are unavoidable, which may be too small to be discovered, and may prove to be too expensive or inaccessible to be repaired. The UARL is also given in gallons/day averaged over a one-year period. By defining and then calculating the volume of the UARL in the system, an indication of the **Potentially Recoverable Real Losses** can be calculated as the difference between the CARL and the UARL. Unfortunately, UARL are very difficult to estimate. However, AWWA/IWA research across a large number of systems, together with actual operating data from many countries has resulted in the development of a relationship between various system parameters and the UARL with statistically good accuracy. The volume of a system's UARL turns out to be a function of the length of the distribution system, the number of service connections, the length of the service lines and the average system operating pressure.

$$\text{UARL (gallons/day)} = (5.41 \times L_m + 0.15 \times N_c + 7.5 L_p) \times P \quad (\text{Eq. 2-2})$$

Where: L_m = Length of transmission and distribution system (miles)

N_c = Number of service connections

L_p = Total length of private pipe (miles)

P = Average pressure in the zone (psi)

Care must be exercised when calculating the UARL for systems where N_c is less than 5,000, P is less than 35 psi or N_c/L_m is less than 32. Field testing of these systems should be undertaken to verify and validate the calculated results. The value of L_p in metered systems is the number of service connections multiplied by the average distance between the curb stop and the customers' meter. In unmetered situations this is the first point of use within the property. In most US systems, this pipe is typically not considered to be "private" pipe but rather is the responsibility of the utility. However, for consistency, the IWA terminology has been used in these definitions.

The **Infrastructure Leak Index (ILI)** is an index recommended by the IWA for establishing utility water loss management targets. The ILI was developed to overcome the shortcomings of other water loss target systems in use and to generate a verifiable target that could be used for management of a water loss program readily comparable to industry benchmarking. The ILI is defined as the ratio between the Current Volume of Real Losses and the volume of Unavoidable Losses.

$$ILI = \frac{CARL}{UARL} \quad (\text{Eq. 2-3})$$

The ILI is substantially different and more meaningful than the frequently used simple ratio between unaccounted-for water and total plant production for comparing system efficiencies.

This latter ratio (unaccounted for water divided by plant production) provides only limited information about the real water loss characteristics of the system. The ratio will not change as operating conditions are altered. In fact it can even appear to improve when actual water losses are increasing. For example, a new subdivision goes on line and the total production increases to meet the additional demand with little if any additional unaccounted for losses. However, the ratio of unaccounted for water divided by plant production will actually decrease as the plant production (the denominator of the ratio) increases even though the total quantity of water loss from the system has not decreased. The system may appear to be more effective than it was the day before the new portion of the distribution system went on line, but in reality, just as much product is being lost as before the addition. Such insensitivity makes this old water loss ratio an ineffective metric for economic or operations planning and is virtually meaningless as a comparison between systems (benchmarking). The ILI calculation includes pipe length and other parameters that adjust for changes to the distribution system and make it more useful as a comparison between different audit periods or even PWSs.

An ILI index of 1.0 indicates that current annual real losses are equal to unavoidable losses and the PWS is operating efficiently when considering real water loss. Actual ILI values typically fall in the range of 1.5 to 2.5 for most PWSs. When a PWS uses the ILI as an evaluation parameter for a water loss reduction project, it must consider the costs it will need to incur and pass on to its customers to reduce its ILI index. Benchmarking is an indicator of a utility's water loss situation with respect to previous audits other utilities; it does not define the acceptability or appropriateness of the loss rate for the particular PWS. Acceptable rates of water loss should be established by the PWS or may be established by regulatory authorities.

2.5 ECONOMIC CONSIDERATIONS OF REAL LOSSES

The objective of a water loss control program is to apply all available techniques to recover as much of the losses as possible. There are limits to what a well-run water loss management program can achieve. Ideally, no water would be lost, however this not achievable in the field. There is a point at which it costs more to locate and fix leaks than is economically justifiable. A balance must be maintained between water loss reduction and costs associated with water loss reducing measures. A PWS can directly affect real water losses by controlling:

- Pressure management;
- Speed and quality of repairs;
- Active leakage control; and
- Pipeline and assets management through selection, installation, maintenance, renewal or replacement.

Figure 2-3 is a graphical representation of the component parts of lost water and the actions that an active water loss management program can use to address these losses.

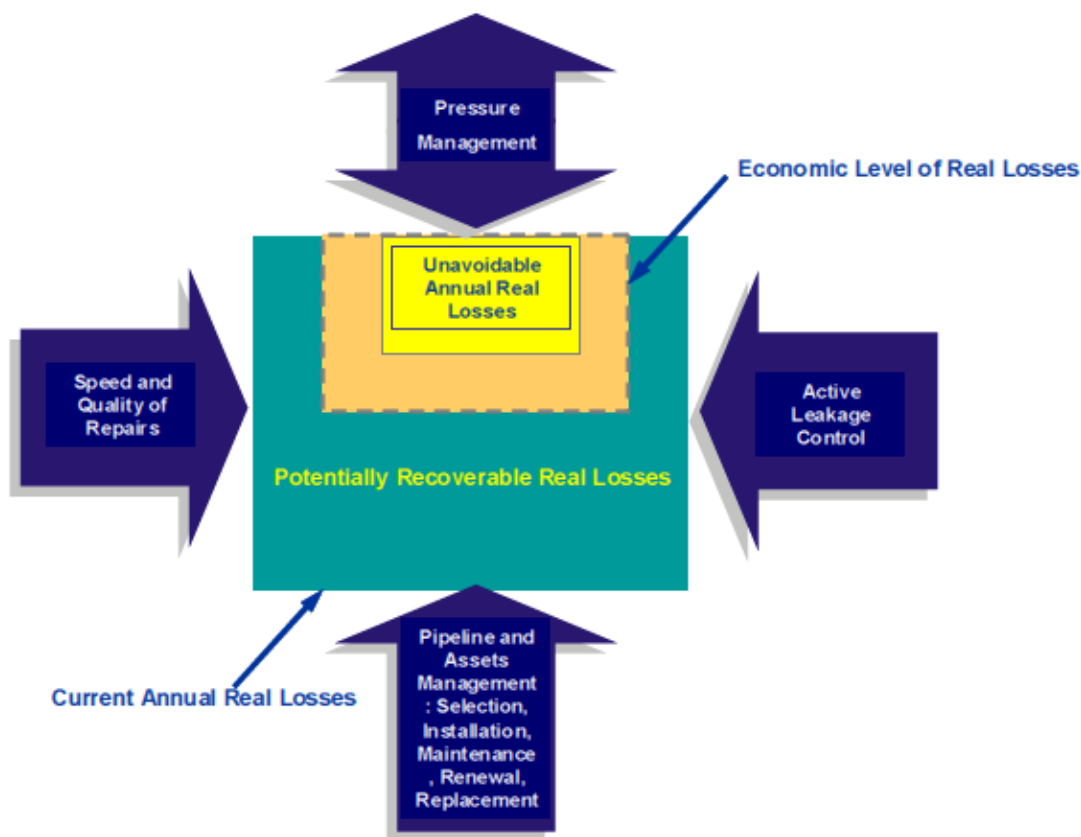


Figure 2-3. Forces Controlling Leakage and Costs

The cost of a leak projected over a specified period of time can easily surpass the initial cost to identify and repair or replace the pipe. The magnitude of the water loss from a site is a direct function of the time it takes to identify, locate and repair the leak. The amount of water lost from a leak or break is equal to the volume of the leak multiplied by the length of time until the leak is stopped and repaired. In Figure 2-4 the boxes represent different stages in the life cycle of a leak. Depending on the size of the leak, time can be the critical factor for each phase. The individual boxes in the figure represent the volume of water lost for that item. A large leak for 10 days at 1,000 gallons a day represents a loss of 10,000 gallons. A smaller 10 gallon/day leak for 1,000 days (around 2 years and 9 months) has the same loss.

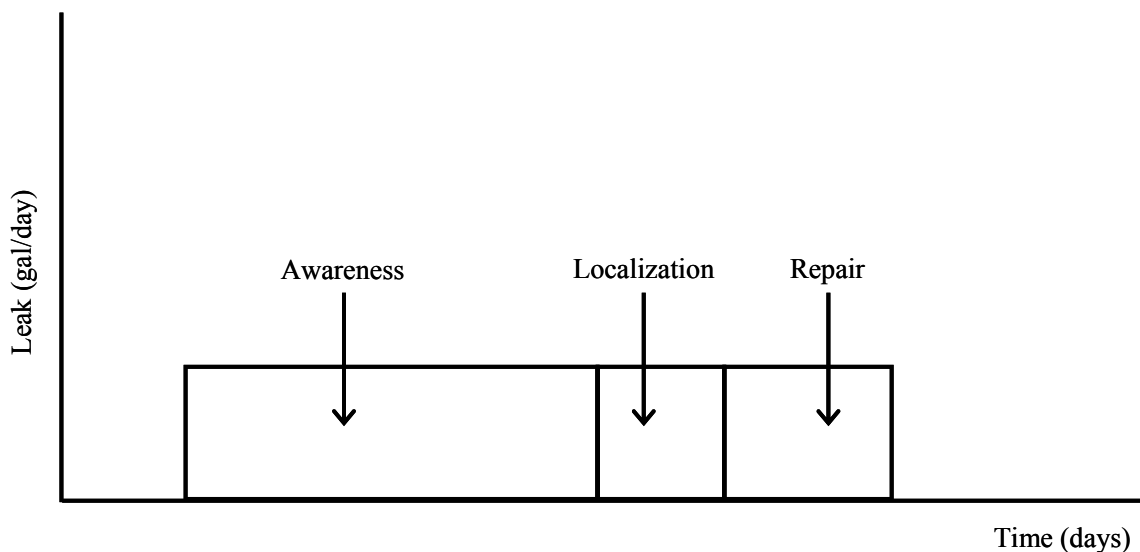


Figure 2-4. Time to Repair a Leak

Source: Based on IWA/AWWA diagrams and IWA Leak Location and Repair Guidance Notes, (2007)

Repairing or replacing a leak includes not only the logistics and operations of manually replacing the pipe but it also involves customer notifications, arrangements for temporary water bypassing or contracting an outside repair source.

Active leakage control (ACL) is the process of proactively searching for leaks that are not yet apparent and repairing them. Pipeline and asset management (AM) are discussed throughout this guidance document.

Asset management involves documenting and evaluating the components of a water utility to determine when the optimum time is to replace or repair a component or pipeline. Evaluation of whether to replace or repair a component not only depends on the economics of replacement or repair but on impacts to the community served such as potential health effects, inconvenience or public opinion and perception of the utility.

Pressure management affects water loss rates. Also, the lack of pressure management has been shown to increase pipe failure rates. These are relatively intuitive ideas since more pressure means greater flow whether it is through the pipe or through a crack or hole in the side of the pipe. Higher pressures mean higher stresses on the pipe. Higher pressure also means higher pressure spikes during pressure surges. These higher values translate into increased failure rates. The management goal is to meet customer pressure expectations, fire flow requirements and adequate pressures to operate the system at as low a pressure as is reasonable.

Each of the methods that a PWS has to address real losses also has an associated cost. In Figure 2-1 the CARL sets the existing losses and associated costs and the UARL establishes the loss reduction a PWS can achieve. The area between is potentially recoverable real losses. The balance of what makes economic sense for a water loss reduction program for the water system lies between these two and is called the **economic level of leakage (ELL)**.

The ELL helps compare costs for making decisions whether a leak detection program will pay for itself or when to repair a pipe versus replacing it. The ELL is the point at which the cost of reducing leakage is equal to the benefit gained from leakage reductions. This can become a very involved process and requires comparing different scenarios. Figure 2-5 illustrates the general approach. The real cost of the volume of water that is lost is proportional to the time that the leak starts until it is repaired. If the leak management program allows for minimal field inspections, the probability of a leak going undetected for an extended amount of time increases. A program with frequent field visits minimizes the time to detect leaks and hence reduces lost revenue and volume of finished water.

The cost to detect and find the leak should also be accounted for in the final estimate. A program with infrequent leak detections will have a very low detection cost per year. Conversely, a program with a frequent detection cycle will experience high annual costs. It is important to point out that this cost does not include the cost of repair since these costs would be very similar regardless of the time it took to detect the leak. The cost per year to conduct a field investigation diminishes exponentially as the number of detection cycles decreases. A parabolic cost curve is formed, rapidly falling from many cycles per year to achieve very low water loss to relatively low total cost per year for programs that are willing to have greater leak loss but only detect infrequently. However, even though a utility may elect to have a frequent detection cycle, there will be a minimum at which no amount of detection effort will find the leaks. At this point, the

cost of detection line (green in Figure 2-5) becomes asymptotic to the “background” leakage levels.

The total cost of leak detection is therefore the sum of these two opposing cost curves. The resultant saddle-curve provides a minimum program range at which the detection frequency is balanced with the amount of water loss from the system. This is known as the ELL range.

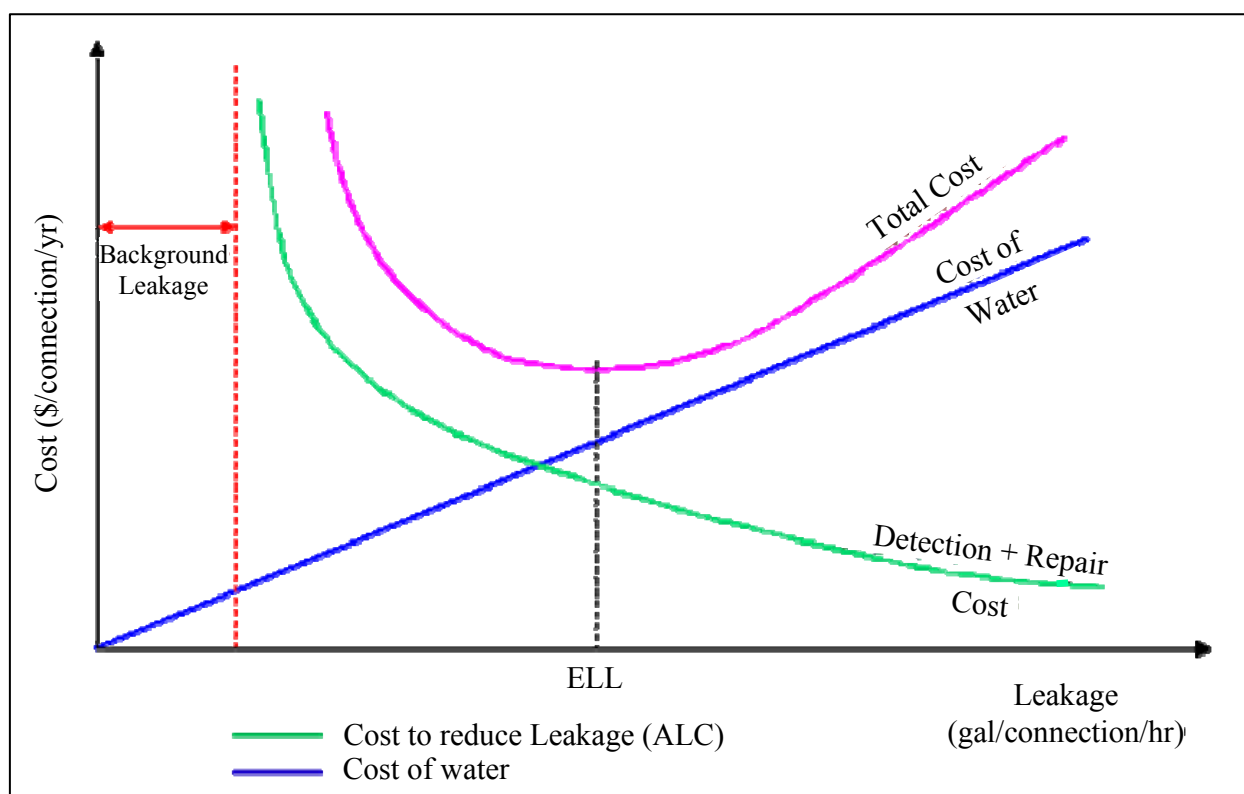


Figure 2-5. An Example of an ELL Curve

3 METERING

3.1 INTRODUCTION

Meters are very important for all aspects of the water audit process. They make it possible to charge customers for the water they use. They record usage and therefore make billing fair for all customers. They can encourage conservation by making customers aware of their usage. They help detect leaks and establish accountability. Meters allow a PWS to monitor treated water output and demand. Meter records provide historic demand and customer use data that is used for planning purposes to determine future needs. In short, metering data makes accurate water auditing possible.

Selection of a meter for a given application depends on many factors including:

- Meter operating principles
- Required accuracy
- Convenience and ease of use
- Volume of flow and flow rate
- Types of flow (laminar vs. turbulent)
- Range of flow
- Installation location and orientation
- Required power
- Data logging requirements
- Durability
- Debris and particle tolerance
- Temporary vs. permanent installation
- Calibration and required maintenance
- Size of pipe
- Type of pipe
- Pressure drop
- Meter orientation
- Flow obstruction tolerance
- Meter reading methods
- Temperature and environment

There is no single type of meter that will accurately measure flow for all applications. A meter has to be selected to meet the location requirements and the conditions where it will be installed. Several types of meters have been developed to meet different requirements. Each of these meter types have advantages and disadvantages. Proper meter selection can be complicated and there are several references that can provide in-depth direction for metering choices and selection including: AWWAs M6 manual *Water Meters-Selection, Installation, Testing and Maintenance* and the Bureau of Reclamations' *Water Measurement Manual* available at http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/index.htm.

Metering is important to all aspects of a water loss control program. Meters provide the data to audit a PWS for water loss, determine where leaks are occurring and determine if intervention is necessary, and establish performance indicators to evaluate the status of water loss within a PWS.

3.2 METER TYPES

There are several ways water meters can be classified but meters encountered in water distribution systems either operate based on principles of positive displacement or the velocity of flowing water. These operating principles as well as some examples of these types of meters are briefly described below. Meters used in water treatment and distribution systems can be further classified in one of five major categories based on the operating principle or use. The five major categories of meters are as follows:

- 1) **Velocity Meters** operate based on measuring the velocity of flowing water through a known cross-sectional area to obtain a flow rate. The volume of water passing through the meter can then be calculated by multiplying the flow rate by the period of time being considered. There are several sub-categories of velocity meters that measure the flow by different methods. They include the following:
 - **Propeller, turbine, paddlewheel and multijet** meters measure the velocity of water by placing an impeller in the water flow. The force of the water on the impeller causes it to rotate at a speed proportional to the velocity of the water. The impeller is connected to gears or an electronic device that computes the flow based on the velocity of the water and the area of the pipe. The method of operation for these meters is mechanical in nature so their accuracy can be subject to wear, interference from debris in the water and mineral or scale buildup on the operating mechanisms. These types of meters require insertion into the pipe, which also requires a pipe tap. They operate more accurately at higher steady flow rates because there can be a slight lag in impeller rotation when starting and stopping, which can reduce accuracy. These meters are best suited for use in larger water mains where flow rates do not change quickly. Some models are smaller and can be used as insertion meters to temporarily monitor flow. Propeller, turbine, and paddlewheel meters are sensitive to turbulence in the pipe (especially smaller meters) and require a straight length of pipe before and after the meter so that the flow becomes steady and non-turbulent. The distance measured before and after the meter is often specified as some number multiplied by the diameter of the pipe so that the specified distances are dependent only on the pipe diameter that is being metered. The length of pipe before and after the meter can range from 10 to 30 pipe diameters.
 - **Ultrasonic meters**, also called acoustic meters, transmit an ultrasonic signal into a pipe at a diagonal angle. The signal frequency that returns to the meter's receiver is altered by the flowing fluid or particles in it. The frequency shift is proportional to the velocity of the water. The flow can then be calculated based on the measured velocity and the cross-sectional area of the pipe. Ultrasonic simply means that the acoustic signal is above audible human detection. There are basically two types of ultrasonic meters, Doppler effect ultrasonic flow meters and time-of-transit ultrasonic flow meters. **Doppler effect flow meters** have one probe that contains both a

transmitter and receiver. Doppler meters rely on suspended particles or air bubbles in the water to reflect the signal. Treated drinking water does not typically contain enough suspended particles for Doppler meters to operate properly and they are not often used for clean water applications. **Transit-time flow meters** transmit an acoustic signal from an upstream transmitter/receiver diagonally through the pipe to a downstream transmitter/receiver. The downstream transmitter/receiver also transmits a signal along the same path to the upstream transmitter/receiver. The difference in the travel times in the signals transmitted from the upstream versus the downstream time is related to the velocity of the water in the pipe. The velocity and pipe size are then used to calculate flow rate. This type of meter may also be referred to as time of flight, time of flow, or time of transit meters. Advantages of this type of meter are: there is no obstruction to flow, they are portable and can be clamped on, there are no moving parts to wear out, they can be used with different pipe sizes and they can measure flow in either direction. Disadvantages include their sensitivity to bubbles and turbulence in the flow and the precise alignment and set up requirements. The pipe material itself, along with the internal and external surface conditions, can affect the signal and therefore accuracy of transit flow meters. These meters work best on cast and ductile iron pipe. Most transit flow meters require an external power source of 90 to 250 volts AC. There are some models that operate on lower DC voltages that can be powered by step down transformer or rechargeable batteries.

- **Electromagnetic flow meters**, often called magmeters, operate based on the principle that water flowing through a magnetic field will produce a voltage which is proportional to the velocity of the water. The measured voltage is then converted into a flow rate. There are two general types of these meters: in-line magmeters and insertion magmeters. **In-line magmeters** are constructed so that the magnetic field is created around the diameter of the pipe. The coils that create the magnetic field and sensing probe are arranged so there is no change in diameter in the pipe and no obstruction to the flow. This type of meter is installed in the pipeline as a permanent short length of pipe. **Insertion magmeters** are inserted into the flow and require a pipe tap. Insertion magmeters form the magnetic field around the probe inside of the pipe. Insertion meters are often used for temporary metering. They have the advantage of being sealed and have no moving parts to foul or wear. In-line magmeters typically require a line voltage power source of 90 to 250 volts AC while the insertion meters can operate on DC currents that range from a few volts to 30 volts.
- **Differential pressure gauges** use a pressure drop that occurs when the water flows through a restriction or around an obstruction in the pipe. The pressure drop is related to the water velocity and from this relationship the flow rates and volumes can be determined. There are several types of meters that operate on this principal, they include: pitot rods, flow tubes, venture tubes and orifice plates. **Pitot rods** are relatively inexpensive insertion meters that are often used for temporary flow measurements. The pitot rod itself forms the obstruction that creates the pressure differential which is used to measure the flow rate. Although pitot rods are often used as temporary meters, they do require a pipe tap for installation. **Flow tubes** consist of

a funnel shaped obstruction placed in the pipe that creates a pressure differential between the large and small opening of the funnel shape. The funnel forms the restriction that creates the pressure differential used to measure the flow rate. The pressure differential in **venture tubes** is created by a gradual narrowing of the pipe diameter followed by a short section of a smaller diameter pipe. The pipe then increases gradually to the original diameter. The pressure differential used to measure the flow rate is measured at the original pipe diameter and the reduced diameter section. **Orifice plates** are round plates with a hole of a specific size bored in them. The plate is placed in the pipe such that the flow has to pass through the restricting hole. Pressures upstream and downstream of the plate are compared to determine the flow rate. By nature of their measurement method, differential pressure gauges restrict the flow in some way and require pipe taps to measure the pressure differential, but they are simple devices with no moving parts and can maintain accuracy over long periods of time.

- 2) **Positive Displacement Meters** separate the flow into known volumes and keeps a running count of these volumes to measure the accumulated flow. The meters use some form of vane, gear, piston, diaphragm or disk to separate the measured volumes. These meters are sensitive to low flow rates and accurate over a fairly wide range of flows. There are typically two types of positive displacement meters used in the drinking water industry, nutating disk and piston meters. These types of meters are used in homes, small businesses, hotels and apartment complexes. They are available for pipe sizes from 5/8 inch to 2 inches. **Nutating disk meters** have a round disk that wobbles or “nutates” around a spindle in a cylindrical chamber. The wobble of the disk in the chamber is caused by the flow of the water. Each rotation represents a specific volume that is registered. **Piston meters**, also known as rotating piston or oscillating piston meters, have a piston that oscillates back and forth as it rotates. The piston is forced to rotate as water flows through the meter. Each rotation represents a specific volume that is registered. Other types of positive displacement meters include reciprocating piston, rotary vane or sliding vane, rotary gear, rotary oval or rotary lobe but these are not common in drinking water distribution systems.
- 3) **Compound Meters** measure over a wide range of flows. The meter contains a velocity meter and a positive displacement meter. The positive displacement meter measures the lower flows and the velocity meter (usually a turbine meter) measures the high flows. A valve regulates which meter is measuring the quantity of water used based on the rate of flow required. These meters can be used in factory settings where demand during production hours is much higher than off hours.
- 4) **Proportional Meters** measure a small portion of the flow in a pipe. Differential pressure techniques are used to divert a small portion of the flow from the main pipe through a meter. After passing through the meter the flow is returned to the main pipe. The flow through the meter is multiplied by a factor based on the pipe size to determine the flow through the pipe. These meters may also be known as fire-line meters, bypass meter, or shunt meters and are most often used in larger diameter pipes. The advantage of this metering method is high flow rates can be achieved with little obstruction or pressure loss due to a meter.

- 5) **Open-Channel Meters** as their name implies measure flow in open channels. There are two major types of open channel meters: weirs and flumes. There are different styles of weirs and flumes but each uses the same principal for measurement. **Weirs** measure the depth of water flowing over a rectangular or notched wall of a known size. The depth of water is related to the flow rate. **Flumes** are a specially designed section of channel. All of the water flow in the channel is directed through it. The depth of flow in the flume is related to the flow rate. Flumes and weirs are designed to be used for open channel flow and are not typically used in distribution systems.

3.3 METERING POINTS

Meters can also be classified by their placement and usage. Meter placement is critical for water audits and leak detection. Six types of meter usage based on placement in the distribution system are described below: master meters, submeters, district meters, component meters, service meters and temporary meters.

- **Master Meters** or **Production Meters** record the output of finished water flowing into the distribution system. A master meter can also be used to measure water being sold from the plant or a take-off point in the distribution system to another system.
- **Submeters** are typically installed by a company or private entity other than the PWS to track or bill water use by an individual process or housing unit. Submeters are installed after the utility owned service meter. A landlord, property management firm, condominium association, homeowners association, or other multi-tenant property might use submeters to bill tenants for individual measured water usage. A PWS does not typically submeter but might encourage submetering programs to promote water conservation. A PWS may also be interested in submetering if a municipality bills for both water and wastewater treatment based on the volume of water that is supplied to the customer. In this billing system, the wastewater is billed on the metered volume delivered based on the assumption that a sizeable percent of the water being metered into the premise is going to be returned as wastewater to be treated. For a user with a large percentage of the delivered water not returned as wastewater, the assessed fee may be reduced based on a submeter reading. The submeter determines the amount of water that is not returned to the system and will not have to be treated as wastewater. A soda beverage bottling plant is one example, since a large portion of the water is bottled and shipped off site.
- **District Meters** or **Zone Meters** measure the water used by a large group of users within a defined area such as a residential or business district. District meters are used to determine if leaks or losses are occurring within the metered area.
- **Process Meters** or **Component Meters** are frequently used to carefully measure chemicals or water used in a process or through specific piece of equipment. Meters at a pumping station could also be considered to fit in this category.

- **Service Meters** or **End User Meters** measure the consumption by water users in the system at the service line (where the line goes from the distribution line to the household). Typically one service meter is positioned on the service line just past its connection with the distribution main.
- **Temporary Meters** or **Portable Meters** can be used wherever it is necessary to determine a flow, confirm meter accuracy, help locate losses, perform field testing or determine a user's consumption profile. These are typically some form of an insertion meter.

3.4 METER REGISTERS, METER READING AND AUTOMATIC METER READING

Meter Registers. The register is the part of the meter that records the volume of water that has flowed through the meter. The register is either mechanically or magnetically linked to the metering mechanism. Most registers display an accumulated total of all water that has passed through the meter after its installation. Many meter manufacturers provide different registers to meet the requirements of their customers. Different registers can record the water volume in units of cubic feet, cubic meters, US gallons, Imperial gallons or liters. In the United States, US gallons or cubic feet are the most common. Registers can also be arranged to record detailed information over a period of time using a device called a data logger. The register can also send the data to a remote data reading device for billing purposes.

Meter Reading. Residential and service meters have a mechanical or digital display for monitoring and recording the volume. Direct read or straight reading meters are the most common meters and have a numerical display similar to the odometer on an automobile and the volume can be read directly. Many of these will also have a hand that sweeps around the dial showing the instantaneous water flow. They often will have a small triangle or star shaped indicator that rotates even at extremely low flows.

This indicator is used to determine if there is a leak occurring downstream from the meter. If all of the water in a metered facility has been turned off and the triangle is still spinning, then there is likely a leak. Some meter models, especially older ones, might have an arrangement of six or seven circular dials on the meter face. These are round-reading meters. Each of the smaller dials represents a multiplier for the number shown on the individual smaller dial face. The multipliers are 100,000, 10,000, 1,000, 100, 10 and 1. Some models may have a large sweep indicator that represents a 0.1

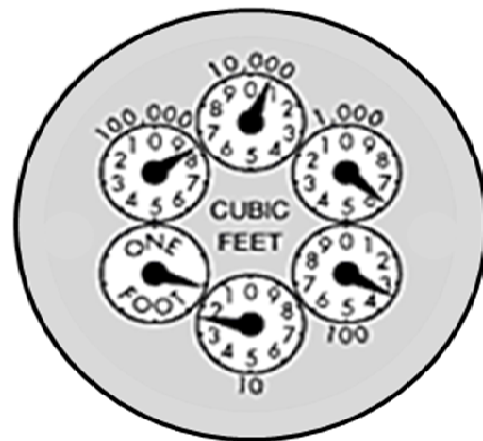


Figure 3-1. This Round-Reading Meter Registers 806323 Cubic Feet

multiplier. The indicators show the number to multiply by. If the arrow is between numbers, use the smaller of the two. The flow through the meter is simply the sum of all of the individual smaller dials. When reading these types of meters, you must pay attention to the direction of the scale numbers on the individual dials. Some of the scales increase in a clockwise direction and some of them decrease in a clockwise direction. See Figure 3-1.

Meter reading occurs on a set schedule based on the billing cycle. Meters are either read manually by a utility worker or read automatically by an Automatic Meter Reading (AMR) system.

Manually Meter Reading require the reader to correctly read and record the metered value. The raw recorded values are then entered into a billing system. Manual read systems are more labor intensive and have higher potential for human error. Errors in manually read meters can allow data errors to affect billing and water audit accuracy. Because manual meter reading is labor intensive, it works best for smaller water systems. Advantages of manual meter reading can include lower initial meter costs and billing system simplicity. Another advantage of manual meter reading includes the fact that the utility's meter reader may spot potential problems before they become serious or locate unauthorized use since they have to visit each meter.

Automatic Meter Reading systems can provide many advantages over manually read meters. AMR is a technology that automatically collects data from the meter and transfers it to a central database for analyzing and billing. Depending on the AMR system used, fewer employees might be necessary for meter reading, less gasoline might be used for the meter reading route and the data can be processed quicker. Some systems can even provide real time trend analysis. Some of the more popular AMR technologies include:

- Handheld data collection where the reader has a data logger that needs to be brought into the proximity of the meter. The meter is touched or “swiped” to download the information to the portable unit that collects the data from the route and is then later downloaded to the utility billing software. This type of system still requires a meter reader to access each meter but reduces recording errors and increases efficiency.
- Mobile data collection is similar to the handheld version but requires the reader to only drive by the general location of the meter that automatically uploads its stored information to the mobile unit. A data logger in the vehicle collects the information via a short-range radio signal.
- Other systems use network technologies based on telephony platforms (wired and wireless) or radio frequency (RF) including WiFi, (a computer protocol), to transmit the data to the central data collection location.

3.5 METERING PROGRAMS

Metering programs involve several aspects of the revenue stream for a PWS. Metering establishes billing procedures and income. Metering and accounting systems can also help detect leaks and other losses. Metering also has aspects that require expenditure including installation, maintenance, calibration, testing and replacement.

The Meter - Billing Relationship. Meters and metering programs are an integral part of billing systems. Many small utilities charge a flat monthly rate for water and might meter only for some large-use customers if at all. Flat rates may be based on type of use such as residential, commercial, industrial or agricultural, or they might be based on occupancy. Systems that use flat rates alone with no metering are usually smaller and might not have the resources to maintain equipment and accounting systems that are necessary for metered billing. A decision by a small PWS to add metering will also involve extra effort to maintain the meters and billing systems.

Larger systems usually have some form of metered billing system. Water rates can be based on customer type or quantity of water used. Rates may increase as proportionally more water is used or actually decrease with increased use. Metering is also used to determine performance and system efficiencies by monitoring specific equipment or areas. Accurate metering is crucial to performing a meaningful water audit.

Establishing a metering program is a good step if you are a small or medium water system and do not have a metering program. While individual customer metering may be out of the financial reach for your system, zone metering may be a way to achieve more accurate billing and gain system operating information at a reduced cost. A PWS must consider available funds for a program and answer questions such as:

- Where do we want metering?
- How many meters will we need?
- What type of meter is appropriate?
- What method of meter reading will we use?
- How do we integrate the new meters into our billing system?
- Is a new billing system required?
- Are the meters upgradeable?
- Does our PWS staff install them or should we have them installed by a contractor?
- Who will test, calibrate, maintain and replace them?
- How do we pay for the program?

Initial capital costs required to purchase and install the meters may come from the operating budget of the PWS, a grant, a tax levy, a water rate increase, or municipal bond. Low interest loans may also be available from a state's drinking water revolving fund. More information about the Drinking Water State Revolving Fund (DWSRF) can be found at the DWSRF web site <http://www.epa.gov/safewater/dwsrf/index.html>. Ideally, the newly installed meters will at least partially pay for themselves in new and recovered revenue.

Installation. Following the manufacturer's installation instructions for a meter is also crucial to proper operation. A properly calibrated meter can register incorrectly if installed improperly. Meter sizing is very important since the accuracy of the meter is dependent on its design type and design flow. Some meter locations require compound meters with dual registers to properly record widely varying flow rates. In some cases, an authorized meter bypass is necessary because the meter restricts flow at higher rates. A bypass might be necessary in emergency situations at industrial, commercial or multi-residential facilities to allow unrestricted flow around the meter for fire control systems.

Calibration and Testing. Over time, most water meters fail to register an increasing proportion of the water flow through them. Under-registration results in lower billing and loss of potential revenue while at the same time erroneously indicating an increased level of water lost from the system. Just as with any mechanical or electrical system, meters are subject to inaccuracy or failure if not installed or maintained properly. Some of the common problems that necessitate calibration and testing of meters include:

- Incorrect installation or sizing,
- Higher or lower flows than designed for,
- Debris in the water,
- Scale build up due to minerals in the water,
- Tampering,
- Environmental extremes including high or low temperature or vibration, and
- Wear.

Meters should be calibrated according to manufacturers' instructions. A PWS should concentrate on testing accuracy of customers who consume more and have larger meters since errors in the larger meters will result in higher revenue losses. Depending on installation methods, residential meters can be tested in place or might have to be removed. Meter testing can be done with portable testing and calibrating equipment or the meters can be sent to a company that tests, calibrates and refurbishes them. Many water systems test only a

representative sample of residential meters and base their decisions to replace or repair meters in a selected area on the results of the tested sample. In their M-36, *Water Audits and Leak Detection* manual, the AWWA suggests 50 to 100 meters is a good number to test. The number of meters tested may need to be larger and depends on the number of meters in the PWS and the statistical confidence levels with which the PWS is comfortable. The more meters that are tested, the more accurate the results will be. State public service commissions often require periodic testing of water meters. For residential meters (5/8 inch) the required testing period can range from 5 to 20 years depending on the state. Larger meters may require more frequent testing.

Replacing. If the PWS has older meters in its distribution system, it might be a good idea to test or replace them. Determining when the optimum time to replace meters and setting up a replacement program can require a complex analysis. An analysis similar to the ELL (see section 2.5) can be undertaken to find the point where a meter replacement program provides the most economic benefit. The optimum point is based on the cost of installation verses the value of recoverable losses. In the past it was recommend that residential water service meters be replaced on a rotating schedule of anywhere from 10 to 20 years but current strategies are more complicated. These strategies are based on: the number of meters in the system, results of meter testing, types and sizes of meters, period of service, water quality, available staff to perform the work, and cumulative volume that has passed through the meter.

Unmeasured Flow Reducers as an Addition to Meters. Another recent development to consider is an unmeasured flow reducer (UFR). Very low flows in some meters may not register, therefore revenue is lost and water audit accuracy is skewed. A UFR is a component that is put in line with the water meter. At very low flows, the UFR changes the flow profile from a continuous flow that does not register on a meter to a pulsed flow that periodically activates the meter. At higher flows the device remains open. Figure 3-2 shows the flow profiles and the UFR valve in the closed and open positions.

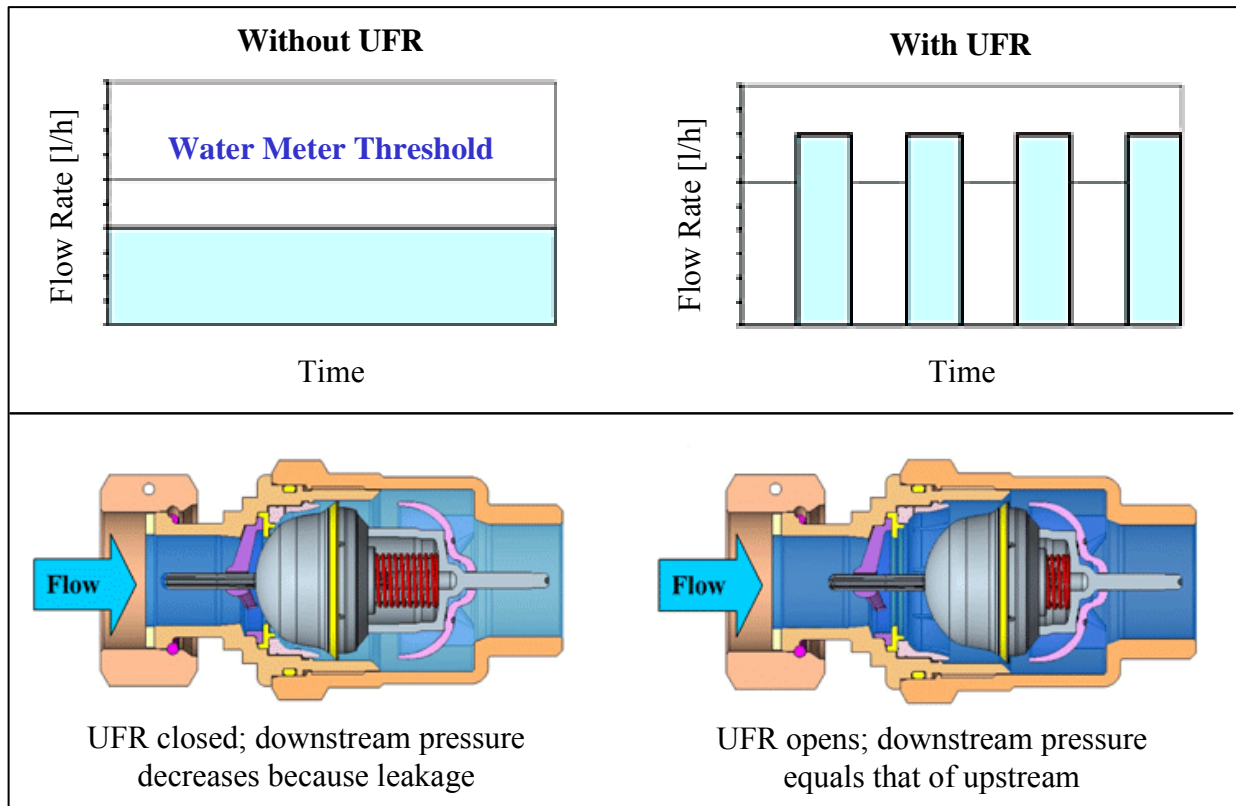


Figure 3-2. UFR Valve Flow Profile and Valve Schematic.

Source: Courtesy of ARI Flow Control Accessories Ltd.

4 WATER LOSS PREVENTION PROGRAM ELEMENTS

4.1 CONDUCTING A WATER AUDIT

Regardless of whether you are in the initial stages of developing a water loss prevention program or already have a well established program, collecting and maintaining information on the elements and condition of components in your distribution system will lead to more accurate water audits. Information collected for a water audit is only the first step and only a portion of the data necessary for a complete water loss prevention program. The knowledge base of potential weaknesses of your distribution system and locations where the most benefit per dollar invested can be achieved will increase as more water audits are performed. When audit results are combined with benchmarks and detailed distribution system data, the PWS management can become more proactive in its operations planning. Chapter 2 provided the definitions and basics to understand a water audit program and conduct an initial water audit. This chapter is intended to help a PWS add accuracy to their water audits. It should also be helpful to provide for a more robust and extensive water loss prevention program beyond the basic requirements.

4.1.1 GATHERING SYSTEM INFORMATION

The effectiveness of your water loss program increases as you expand the type and amount of information that is collected. Table 4-1 shows some of the distribution system details that should be collected and maintained. In addition to piping information, data should be maintained for other components within the water system including: meters, valves, storage tanks, fire hydrants, pumping and pressure boosting stations, and distribution system controls and monitoring equipment. While all of the data maintained for a distribution system can provide valuable information, maps showing the locations of the assets are critical.

Asset management, data storage, and organization can be as simple as a log book or spreadsheet. EPA has developed the *Check-Up Program for Small Systems (CUPSS)* to assist with asset inventory and management activities. CUPSS is a free, easy-to-use, asset management tool for small drinking water and wastewater utilities. CUPSS provides a simple, comprehensive approach based on EPA's highly successful *Simple Tools for Effective Performance (STEP) Guide* series. Use CUPSS to help you develop:

- A record of your assets,
- A schedule of required tasks,
- An understanding of your financial situation,
- A tailored asset management plan.

More information on CUPSS can be found at <http://www.epa.gov/cupss/>. A brief description of the CUPSS software and some screen captures from the program can be found in Appendix D.

Table 4-1 Data Requirements for a Detailed Management Plan								
Physical	Exist	New	Performance	Exist	New	Commercial/Service	Exist	New
Year of Installation	Y	Y	Complaint Frequency	A	Y	Critical Customer	Y	Y
Diameter	Y	Y	Type of Complaint	A	Y	Affect on Community	Y	Y
Material	Y	Y	Break Frequency	A	Y	No. of People Served	A	A
Length	Y	Y	Type of Break	A	Y	Length of Shutdown	A	A
Location	Y	Y	Reason for Break	A	Y	Coordination w/Others	A	A
Interior Lining	A	Y	Service (hydraulic) Adequacy	Y	Y			
Exterior Protection	A	Y	Fire Flow Adequacy	Y	Y			
Joint	A	Y						
Wall Thickness	A	Y						
Soil conditions	A	A						
Internal Condition	A							
External Condition	A							
Y = yes, in all cases A = as needed, or as available								

Source: Based on (USEPA, 2002) Deteriorating Buried Infrastructure Management Challenges and Strategies

4.1.1.1 Mapping – CADD & GIS

Determining size and location of a water system's piping and other assets is the first step in data gathering. Almost all systems will have an existing map of their water lines and assets. Some systems use hardcopy maps while others use their own Computer Aided Drafting and Design (CADD) system or Geographic Information System (GIS) packages to update the distribution system inventory. Mapping software packages range in price from a few hundred dollars to several thousand dollars. CADD and GIS software can help keep necessary information current and easily accessible. The ideal tracking tool will depend on the complexity of the distribution system and the sophistication of the tracking that a PWS needs. There are some lower cost and free CADD and GIS software packages available for water system managers who want to begin electronic mapping with minimal expense.

4.1.2 ESTABLISHING PERFORMANCE INDICATORS

A proactive water loss control program requires that a water audit is completed and performance indicators and benchmarks are established. This guidance document concentrates on performance indicators related to control and mitigation of water loss in the drinking water distribution system but when establishing performance indicators and benchmarks, the PWS administrators should consider other potential benchmark categories.

Section 2.4 of this guidance document defined performance indicators and benchmarking and discussed the CARL, UARL, and ILI as indicators of the status of the distribution system. The CARL, UARL and ILI are operational performance based indicators and would be recorded as performance indicators in the *water system performance* benchmark category. Other examples of benchmark categories a PWS administrator should consider include: *financial performance*, *customer satisfaction*, *employee safety*, and *employee training*.

Each PWS is unique so establishing performance indicators and benchmarks will be dependent on the priorities and goals set by the water system administrators;

however the general steps are

shown in Figure 4-1. There are many free or low cost performance indicator and benchmarking software programs from drinking water agencies around the world that are available on the internet to simplify instituting a benchmarking program. For more information on benchmarking and discussion of some of the available benchmarking software programs, see the publication *D20 Benchmarking Tools*, from the European Commission's Tools for Integrated Leak Detection (TILDE) program (EC Contract No. IPS-2001-42077 December 2005). It is available at: <http://www.waterportal.com/comunication/document/D20Benchmarkingtools.pdf>.

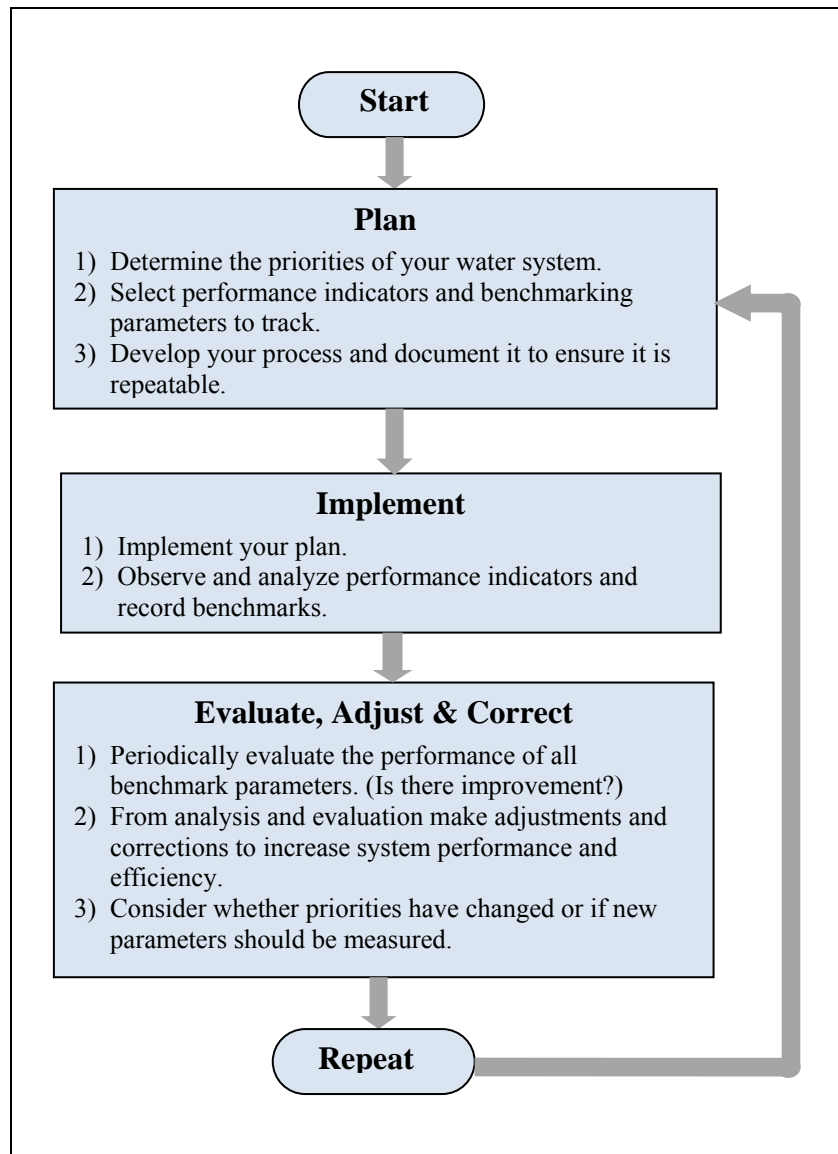


Figure 4-1. The Benchmarking Process.

4.1.2.1 Assessing Losses and Data Gap Analysis

Once baselines have been established, undertake an analysis to determine where water loss prevention improvements can and should be made. Start with the obvious problems that can be remedied within budget then examine larger issues that may involve further analysis or a large financial investment. Review and compare your options through economic level of water loss and other financial analyses then prioritize needs. Once a course of action has been selected, the PWS should arrange financing and set schedules to complete the task.

4.1.3 COMPARING LOSS CONTROL OPTIONS

In addition to the economic level of water loss as a tool to assist in assessing losses, cost/benefit analysis between options is extremely useful. Cost/benefit analysis allows for direct comparison by converting all aspects of competing options to present dollar values so they can be compared on an equivalent dollar for dollar basis. An option that should be included in nearly all cost/benefit analysis comparisons is the option of “taking no action.” When discussing a leak prevention program, the “take no action” option compares the cost of a leak over a period of time to other optional interventions and loss control options.

4.2 INTERVENTION

4.2.1 FURTHER INFORMATION GATHERING

Both water audits and performance indicators will identify operational areas where more data should be collected. Periodic water audits and performance indicator reviews will help to isolate where losses are occurring and how much is being lost. In many cases it may be necessary to install additional meters, establish DMAs or review records in greater detail to further narrow the physical search effort for losses.

4.2.2 LEAK DETECTION AND LOCATING

4.2.2.1 Locating Leaks and Losses Through Records

It is possible to spot losses through billing data discrepancies or abrupt changes in amounts of water that have been historically used. Some existing billing software packages have built in functionality to flag historical water use changes. Desktop spreadsheet software can also be programmed to flag water use changes with a little effort. AMR systems that can track and show usage profiles at more than monthly or quarterly billing intervals may also be instrumental in finding either real or apparent losses. Sudden increases in meter readings may be a sign of leakage, theft or an open valve that should be closed.

Accounts that have been estimated but not read for several billing periods should also be reviewed since the estimated usage may be quite different from the actual usage. It is prudent to re-calculate assumed estimates periodically to ensure that water usage patterns in the area have not changed when meters are not available to correlate the data.

4.2.2.2 Physically Locating Leaks and Leak Detection Approaches

Identifying system leaks can pose a challenge. While operating personnel might identify some leaks in the distribution system during routine field inspections, not all leaks are visible. Planned maintenance will help identify leak occurrences. To better understand how water leaks are detected, water managers should look at three major water loss leak detection categories: (1) leak detection through appearance, (2) leak detection through flow monitoring and, (3) leak detection aids (acoustic, thermal, electromagnetic, tracer, etc.).

Leak Appearance

AWWA estimates that the average lifetime of a slowly developing leak, from its inception until its repair averages two years (AWWA M36, 1999). Development of a leak depends on many variables and not every leak is immediately detected. The presence of a leak in the distribution system is often identified only when it appears on the surface and is reported by a utility employee or customer. This mode of detection is very valuable. An educated and motivated customer, as well as a trained field inspector, is an indispensable resource for this mode of detection. Appearance of a leak may take a variety of forms from the subtle to the spectacular. The ways that leaks may be recognized and reported in the field include:

- **Suspect Areas** - This is perhaps the subtlest of appearances and may go unnoticed for some time. Educating customers on what to look for sensitizes them to consider unanticipated moisture as a possible leak and report it. The leak may manifest itself as a moist or discolored area, especially if it is in the vicinity of the water main, service line or meter. In some climates, this indicator may not be standing water but rather may be an unusually green patch especially during dry summer months.
- **Surface Flows** - Water appearing on the surface of the ground in quantities sufficient to cause a flow may portend a leak that has become large enough to make it to the surface in such a quantity that it is not being absorbed by the surrounding soil or evaporating. Flows around hydrants can often signal an improperly seated foot-valve or a damaged connection. While such flows may be from naturally occurring ground water flows, they may also need special attention from the water provider to identify their sources. Typically, a simple chlorine (or fluoride) residual test can determine if the flow is potable

water. Flows in culverts or entering streambeds may not be immediately recognized as leaks from the public water system as one expects to see flowing water in these locations.

- **Reduced Water Pressure** - Customers are highly sensitive to changes in their service and expect their water utility to provide excellent water quality and reliable flow. If a leak has grown large enough, the system might experience a notable loss of pressure. While a very gradual loss of pressure over time is hard to recognize, increased reports of “unacceptable” pressures within an area should be a signal the leak may have reached actionable levels.
- **Flow Disruption** - Probably the most dramatic form of water loss detection is due to the sudden failure of the main and loss of service. The provider is typically notified of such occurrences as they tend to be highly visible and may become a public safety issue. This water loss has moved from the category of a leak to being a true system failure that has the potential to impair both the water quality and flows. System operators are often aware of such failures, even if its exact location is unknown, through loss of system pressure or storage tank level. If not located in a visible area, larger water main failures may be reported through user complaints of low pressure and/or discolored water.

4.2.3 FLOW MONITORING

One of the major methods of water loss detection is through system measurement. Water loss may be detected from routine water meter reading and billing computations by the customer service department. System water loss may also be recognized by the customer when higher than expected water bills are received if the leak is in the service line on the customer’s side of the water meter. Water loss identification through metering requires the comparison of water volumes recorded by the collective customers’ meters over a specific period of time to the water volumes discharged from the treatment facilities or the volume passing through system zone meters over this same period of time. Such comparisons require training, communication and management attention. Customer service billing activities and system flow monitoring operations are not compared in many utilities as each set of data serve a unique and different purpose. Management must provide the leadership and incentive for these comparisons to be made and the result analyzed for metering to become an effective tool in the water loss identification.

Water volume measurement may also be the result of a program established to meter flow volumes in isolated portions of the system to actively seek out real water losses. Such an approach subdivides the distribution system into areas that can be isolated from each other and

whose flows can be measured with appropriate metering. The size of each District Meter Area (DMA) is a function of the system configuration, size of the labor force, hydraulics of the area and customer demand patterns. Typically a DMA will serve 1,500-2,000 connections. Once a DMA has been identified, the flow is metered with an installed or portable water meter to measure the total volume of water supplied to the area. Reading the DMA master meter during late night periods (2:00 am – 5:00 am) can provide indications of higher flows than would be expected during this early morning period. DMAs with suspiciously high flow levels can then be further refined through step-testing to better characterize the water loss in this area.

Step-testing further subdivides the DMA under consideration by measuring flows in individual, isolated laterals of the area. This testing starts at the end of the system and successively works backwards towards the head of the area where the area meter is located. A comparison of the measured results, coupled with knowledge of the area, can flag laterals in the system showing a higher than expected flow rate and one where leak detection is most likely.

Step-testing can use either permanent or temporary metering. Permanent meters have the advantage of already being in place, easily accessible with historical usage data based on past billing to verify their calibration. Key points in the distribution system, which will be needed for routine analysis of system flows, are good locations for permanent meter installation. Such meters can be routinely read either manually or via a supervisory control and data acquisition (SCADA) system. Frequently these meters are used to monitor flows throughout the system but can double as water loss meters when used as part of a water loss management program. Permanent water meters require a substantial capital investment to install and maintain. Unless it can serve dual and repetitive functions, permanent DMA meters may be financially infeasible for some systems.

Alternatives to fixed meters are temporary portable meters. Many of these meters are available as “clamp-ons” that measure the volume flow rate through a water main by being attached to the outside of the main. The obvious advantages of this type of temporary meter is that the integrity of the pipeline system remains intact and the meter can be placed and then relocated to another spot when measurements are completed. Further, if the water main is readily accessible (e.g., meter vault, pressure release valve (PRV) site, air release vault), the need to excavate the line is avoided. Care must be taken to understand the accuracy of clamp-on meters and their sensitivity to the flow rate thresholds when used to detect water loss.

Several general categories of temporary flow meters are shown in Table 4-2. Each of these sensor types requires a processor to integrate the signals and translate them to a liquid flow rate. It should be noted that these meters could be used for single point readings or as part of a

remote-read, long term monitoring scheme. A Supervisory Control and Data Acquisition (SCADA) system can be a highly effective communication and processing network for such metering.

4.2.4 LEAK DETECTION AIDS

Perhaps the most common form of water loss leak detection is from proactively searching for leaks in the field. Searches must be planned carefully and conducted in a disciplined manner for the results to be meaningful. These searches use a wide variety of tools to aid in discovery of potential system leaks. Most of these leak detection approaches locate and quantify the leaks by observing the presence of, or change to physical property (noise, temperature, etc.) that occurs only when a pipe leaks. Understanding the strengths and weaknesses of each approach can help the operator select the best application for the system. A number of these technologies are discussed below.

The integrity of underground infrastructure is always difficult to evaluate. A large part of the capital investment of a public water utility can be attributed to its underground assets. Due to low visibility they are easy to forget, hard to assess but absolutely critical to the sustainability of the utility. The utility should actively search for leaking water mains, evaluate the magnitude of these leaks and have a program in place to prioritize and address leaks. Since a direct measurement of the leak's flow rate is difficult, secondary indicator measurements that are frequently easier to apply can be used as surrogates. These secondary measures typically fall into a number of techniques: acoustic, thermal, electromagnetic and chemical. Each technique has its own strengths and weaknesses. Not all leak detection techniques can determine where the leak is located and even fewer can assess the magnitude of the leak.

Some leak detection methods discussed below may require dewatering of pipes to install sensors or equipment. When using a leak detection method that requires dewatering, it is likely that disinfection and testing of the dewatered section will be required before the water line is put back into service. This ensures that no source of contamination has been introduced to the water supply by the testing procedures. Contact your state or primacy agency for their requirements for disinfection and testing after dewatering pipelines.

Table 4-2. Temporary Flow Meter Types			
Meter Type	Operating Principle	Notes	
Ultrasonic	Utilizes “time-of-flight” measurements of wave propagation (Doppler shift) of an applied ultrasonic signal to determine the fluid velocity.	Advantages	Highly accurate flow detection for stable flows.
		Disadvantages	<ul style="list-style-type: none"> • Not accurate in regions of temperature change. • Requires 1 100-240VAC, 50-60 Hz power source.
		Accuracy	+/- 1%
		Cost	Capital: \$3,000-\$4,000
Magnetic Induction	Relies on the conductive properties of the liquid. The flow passes through a magnetic field producing a voltage difference over the cross-section of the flow area proportional to the average flow velocity. By knowing the liquid conductivity, and the magnetic field strength, the flow velocity can be calculated.	Advantages	Relatively inexpensive and accurate across a wide range of flow rates.
		Disadvantages	<ul style="list-style-type: none"> • Requires 1 100-240VAC, 50-60 Hz power source. • Must be inserted in-line (flanged connections).
		Accuracy	+/- 0.5%
		Cost	Capital: \$2,500-\$4,000


4.2.4.1 Acoustic Devices

Two distinctive audible noises are produced as pressurized water breaches the water main. The first noise is produced by a shockwave created when the water is forced through the opening. (The differential pressure between forcing the water out of the pipe must usually exceed 15 psi for substantial audible sonic waves to be generated and therefore detected.) These sounds are normally in the 500 to 800 Hz range and are propagated through both the pipe and the water. These sonic waves travel substantial distances in the pipe and therefore can be detected for hundreds of feet from the actual break site. The second noise generated is typically in the 20 to 250 Hz range and is produced by the impact of the water stream on the surrounding pipe bedding materials, as well as water circulating through the cavity caused by the leak (Hammer and Hammer, 2003). These sound waves travel through the ground and are therefore restricted to a much shorter distance of travel before they are attenuated and can no longer be identified from the background noise. These lower frequency sound waves can be used to help spot the exact location of the break as the operator continues to listen along the pipe. There are many sounds carried by the pipes such as the noise of water moving through and around various appurtenances, to pumping sounds to street noises. Every distribution system has its own unique

acoustic signature that changes from one point in the system to another. It takes time to recognize and understand the various noises that are part of normal system operation. Acoustical instruments are designed to assist the operator in detecting and identifying those sounds that are most characteristic of a main water loss. An experienced operator with distribution system operating knowledge is a key factor in effective leak detection.

Listening Rods/Sticks

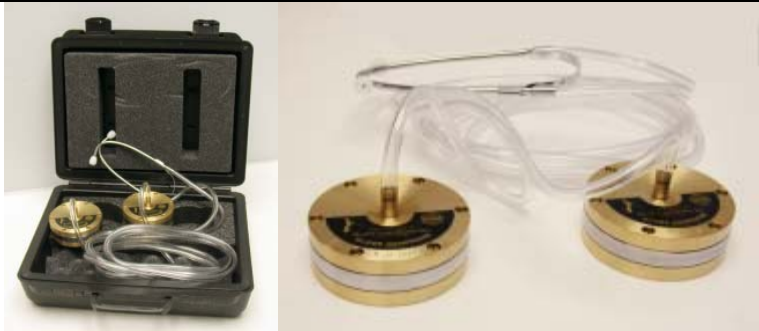
Listening rods are among the simplest and oldest form of leak detectors in use. A listening rod aids the user in hearing the noises that water makes as it is forced from a pipe. The listening rod in its simplest form is a steel rod, several feet in length, with an earpiece at one end to help block out outside noises. The tip of the rod is placed on the pipe if exposed, or more frequently on a hydrant or valve stem. Sounds from the water loss site are transmitted through the steel rod to the listener. If the user is in close enough proximity to the leak site, the lower frequency ground waves can also be detected. It takes operator practice and skill to successfully use a listening rod, but it is an effective and inexpensive tool. Table 4-3 provides more detail regarding listening rods/sticks.

Table 4-3. Listening Rods/Sticks	
Prevalent Application	Leak Detection
Strengths	<ul style="list-style-type: none"> • Simplicity • Rugged, no mechanical parts, no electronics • Requires no calibration
Weaknesses	<ul style="list-style-type: none"> • Requires substantial practice to use well • May be hard to differentiate between normal and leak noises in noisy systems • Hard to pinpoint location of leak
Set-up Time	1-2 minutes – time it takes to apply to top of hydrant or open and a valve box and expose top of isolation valve
Average on-station time	2-5 minutes (varies) – highly dependent upon skill of operator and familiarity with the sounds of the system
Capital Cost	\$15-\$25, w/case \$50 - \$60
Photo	 <p>Ref: www.pollardwater.com/pages_product/P679sonoscope.asp</p>
Notes	The experienced water system operator can become very adept detecting smaller water leaks using a simple contact listening device. However, the detection of larger leaks and the location of any leak can be very difficult.

Geophones

The geophone is a completely mechanical listening device that operates much like the physician's stethoscope. A set of listening tubes extends from the operator's ears down to listening-heads placed directly on the ground above the pipe to be evaluated. An experienced operator, moving the heads along the pipe, can become adept at detecting leaks. The stereo-effect of the two listening heads permits the operator to accurately locate the site of the breach. While the simplicity of the device makes it very rugged and inexpensive to operate in the field, it can miss some sounds that are traveling in the pipe and water system. Leakage sounds for non-metallic pipe or the low-frequency sounds of water impacting the surrounding bedding do not travel well through the pipe but rather travels through the ground. Geophones are best used for

detecting leak sounds that are propagated largely through the ground. Table 4-4 provides more detail regarding geophones.

Table 4-4. Geophone Leak Detection	
Prevalent Application	Leak detection and location
Strengths	<ul style="list-style-type: none"> • Simple and ease of use • Rugged construction • Requires no power
Weaknesses	<ul style="list-style-type: none"> • Requires operator experience to become proficient • May miss some classes of leaks • Pipeline route needs to be marked so that operator can place phones directly above line
Set-up Time	5-minutes – some unpacking and assembly on first test required.
Average on-station time	2-5 minutes for leak detections with another 5-20 minutes for leak location.
Capital Cost	\$350 - \$400
Photo	 <p>Ref: http://www.heathus.com/InfoCenter/geophone.pdf</p>
Notes	Once a leak sound has been detected, the two listening heads are placed on either side of the suspected leak site. By careful listening to the difference in sound intensities, the experienced operator can isolate the general area of the leak.

Hydrophones


There are a wide variety of acoustic listening devices that use a hydrophone (piezoelectric crystal materials that produce an electric signal in response to acoustic impacts) to pick-up the sounds of leaking when placed on the piping system or in some cases on the ground above the pipe. These instruments are enhanced versions of the listening rod coupled with a battery powered sound amplifier to enhance the sound being transmitted. Testing on the ground along the pipe must augment the static listening to the pipe leak sounds to accurately locate these leaks. Many

devices are also equipped with frequency range filters to permit the operator to filter out non-leak causing noises and better concentrate on noises coming from the pipe in the frequency range most indicative of a leak. A number of more sophisticated acoustic leak detectors have added various degrees of digital processing to the amplification systems. These detectors aid the operator by providing digital and graphic readouts of sound strength to assist in identifying leak locations. Many instruments attempt to correlate the amplitude of the leak noise to leak flow rates to provide the operator with an indication of leak magnitudes.

While the hydrophone greatly adds to the ability to detect leaks, operator experience and judgment is needed to understand the testing intervals that are needed along various sections of the system. The distance that leak sounds will travel and can be detected depends on both the pipe material and diameter. Table 4-5 provides an indication of how these detection distances vary and Table 4-6 provides more detail regarding hydrophones.

Table 4-5. Leak Noise Travel for Distances in <u>Distribution</u> Mains* (for a 5 gpm leak @ 60 psi)		
Type of Pipe	Pipe Dia.	Typical Sound Travel Distance
Iron Pipe	6"	1000 – 1200 ft
	12"	800 – 1000 ft
	24"	600 – 800 ft
AC Pipe	6"	800 – 1000 ft
	12"	700 – 900 ft
	24"	400 – 600 ft
PVC Pipe	6"	400 – 600 ft
	12"	200 – 300 ft
	24"	100 – 150 ft
Leak Noise Travel Distances in <u>Service</u> Lines (for a 2 gpm leak @ 50 psi)		
Copper Tubing		600 – 1000 ft
Galvanized Steel Pipe		800 – 1200 ft
"Poly" Plastic Tubing		50 – 100 ft

*Courtesy Subsurface Leak Detection, Inc., 4040 Moorpark Avenue, Suite #104, San Jose, CA 95117


Table 4-6. Hyrdophone Leak Detection	
Prevalent Application	Leak Detection, location and quantification
Strengths	<ul style="list-style-type: none"> • Numerous operator aids to enhance leak detection and location • Can better fix location of water loss • Some detection heads can be designed to optimize use on non-metallic pipe
Weaknesses	<ul style="list-style-type: none"> • Requires some operator training • Requires experienced operator to interpret what is being heard • Equipment needs moderate care in the field • Higher cost
Set-up Time	5-minutes – some unpacking and assembly on first test required. Time it takes to apply to top of hydrant or open a valve box and expose top of isolation valve
Average on-station time	2-5 minutes for leak detections with another 5-20 minutes for leak location.
Capital Cost	\$1,200 - \$4,000 depending on features
Photo	 <p>Ref: http://www.subsurfaceleak.com/PDFs/LD-15_brchr.pdf</p>
Notes	Specialized listening heads are available to connect directly to the pipe (valve or hydrant) or for use on the ground above the pipeline.

Acoustic Fiber Optics (AFO)

There has been some recent research using listening devices either a fiber optic cable [Higgins and Paulson, 2006] or hydrophones arrayed along an insulated copper cable that are streamed into the water main at a valve or other fitting. Primarily used in larger transmission mains, the listening devices are placed as a permanent or quasi-permanent installation in key water mains that are critical to the reliability of the system. The cable detects sounds that are transmitted to a digital processing and recording device. Circuitry in the digital processor filters-out random and system noises, focusing on noises most frequently associated with pipeline breaks. Once a break is detected, its location along the cable is provided to the operator.

Acoustic Fiber Optics (AFO) are frequently used with larger diameter prestressed concrete cylinder pipe (PCCP) due to the distinctive “ping” that is made when a pre-tensioning wire breaks. A profusion of such wire breaks over a relatively short period of time may be a precursor to a rupture of the pipeline in that area. These systems when properly installed and monitored can be an effective element in an overall water loss management program. AFO installation requires dewatering of the distribution system site, but not necessarily the complete dewatering of the entire system. Cable lengths exceeding 40 km have been used. Cable receiver and processing equipment must be provided with an external power source for continuous operation but lend itself to SCADA interface.


A laser is used to project light down the fiber and a data acquisition system monitors reflections generated by the acoustic activity in a pipeline. The entire fiber cable acts as a sensor so in effect, the sensor is never further than a pipe diameter from a pre-tensioning wire break. An advantage of the system is that no electronics are placed in the water flow, so monitoring system noise is nearly eliminated. Table 4-7 provides more detail regarding AFO cables.

Table 4-7. Acoustic Fiber Optic Cable	
Prevalent Application	Detection of small leaks before they become major. May be a good approach for exceptionally critical mains that cannot be taken out of service to repair main failures or major leaks.
Strengths	<ul style="list-style-type: none"> • Provides long, continuous record of main integrity. • Can be highly accurate in detecting and locating water leaks. • Can track growth of leak site size to accommodate economical repair schedule. • May not have to be dewatered, but pressure must be removed to place the cable.
Weaknesses	<ul style="list-style-type: none"> • Requires unidirectional flow to prevent cable from becoming entangled in valves and fittings. • False positive and negative readings.
Set-up Time	12-18 hours installation time depending on size and complexity of main.
Average on-station time	30-60 days. Can also be set up as a permanent in situ system listening for changes in the main noises that may indicate the formation or growth of water loss sites.
Costs	Typically a contracted service, equipment not owned by the utility. Service contract placement / removal costs of \$2,000 - \$10,000 plus monitoring costs of \$15-\$25 per foot of main. Utility must also dewater line and open access pits.
Photo	 <p>Ref: http://www.puretechnologiesltd.com</p>
Notes	Many of these systems are proprietary and may only be contracted as an occasional or ongoing service. Cost includes monitoring (active listening) and analysis by the contractor over an extended period of time with periodic reports of findings. Installation may require disinfection and testing before the pipeline is placed back into service.

Electromagnetic Field Detection

Electromagnetic (EM) field detection is a proven proprietary electromagnetic inspection technology for evaluating the current condition of pre-stressed concrete cylinder pipelines (PCCP). Owners of water pipelines can use EM technology to identify distressed pipe sections within their infrastructure, which allows them to target their maintenance, repair and replacement programs. Once a pipe is dewatered, EM equipment can be deployed to locate and quantify existing wire breaks along individual pipe sections.


A mobile energy head generates an electromagnetic field inside a PCCP and measures the changes within this field caused by broken wires. By providing information on the number of broken wires in each pipe, EM detection enables the most effective remediation strategy to be put into action. This process is often used as a first step in a long-term management program for pre-stressed pipelines. Once the survey is completed and the current condition of the pipeline is determined, a long-term acoustic monitoring program can be instituted. This monitoring program, in conjunction with a GIS-based structural risk management program, can ensure the long-term integrity of the asset. Table 4-8 provides more detail regarding EM field detection.

Table 4-8. Electromagnetic Field Detection	
Prevalent Application	Similar to acoustic monitoring, electromagnetic field detection is a technique for surveying, mapping and evaluating the integrity of PCCP pipe.
Strengths	<ul style="list-style-type: none"> • Generates record of PCCP water main integrity. • Non-destructive test can spot broken wires before they appear on the surface.
Weaknesses	<ul style="list-style-type: none"> • Pipeline must be dewatered. • Pipeline may have to be disinfected and tested before being placed back into service. • Interference from adjacent metallic pipelines may occur.
Set-up Time	24-48 hours depending on size and complexity of main, time to dewater main, time to excavate service pit at both ends.
Average on-station time	Set-up time: Requires that line entry and exit points be uncovered, line dewatered and line opened. Preparing the line, inspection and equipment insertion can take 1-2 hours. The inspection takes about 15-min / 1,000-ft of water main to be inspected (assumes straight, unencumbered path).
Capital Cost	Actual inspection and analysis costs average \$15,000-\$30,000 / mile of pipeline to be inspected (exclusive of the on-site work required to prepare the pipeline for inspection). Process is proprietary and must be contracted.
Photo	 <p>Ref: http://www.puretechnologiesltd.com</p>
Notes	A two-tier analysis is typically provided. A qualitative analysis of the data takes about 2-days to return to the utility and permits immediate repairs as needed before line is placed back into service. A longer, 30-day detailed analysis is then provided the utility.

Data Loggers

Data loggers are a modification of an acoustic leak noise detection recording. Data loggers combine a listening head with a digital recorder into a single sensor that can be attached to the system and left in place to operate over an extended period of time. At the end of the testing period, the loggers are removed and their time-marked data downloaded to specialized leak characterization and detection software for analysis. The frequency of sampling and recording sound intensity information is preset by the operator and can range from once per millisecond to once per minute and can remain in place for several days, limited only by the data storage capacity of the unit. More sophisticated loggers can be set to turn on and turn off, sampling only during the quieter, low-flow hours. Some models of data loggers contain radios that will download their stored data when queried, resetting themselves for follow-on recording. This data transmission feature is useful for extended period measurements when the change in identified signals can be used to confirm and quantify water loss magnitudes. Data loggers can be an effective, low-cost method of taking continuous measurements, especially when nighttime logging is desired.


Data loggers are most successful when used for leak detection on cast iron, ductile iron, steel, concrete and transit pipe. Leak detection in PVC needs longer run times. Table 4-9 provides more detail regarding data loggers.

Table 4-9. Data Loggers	
Prevalent Application	Leak noise sound intensity sampling and recording.
Strengths	<ul style="list-style-type: none"> • Provides long-term record over several days. • Requires no on-site operator. • May be used with other loggers to quantify and locate leaks. • Requires limited operator training to set logger in field.
Weaknesses	<ul style="list-style-type: none"> • Subject to easy theft unless protected.
Set-up Time	20-30 minutes, including time to set logger sampling rate and recording period. Required revisit to download and/or remove data logger.
Average on-station time	1 – 3 hours depending on pipe material. PVC requires longer data collection periods.
Capital Cost	\$19,000 - \$21,000 (includes factory training).
Photo	 <p>Ref: www.subsurfaceleak.com</p>
Notes	These devices are most accurate for leaks in pipes < 16" and are more difficult for leak detection in pipes > 36". For the most accurate leak locating, more than a single correlation should be used for each leak detected.

Leak Noise Correlators

It is not unusual for larger leaks to generate both lower frequency and lower noise intensities than recently formed, smaller leaks. Smaller pipe penetrations may result in higher discharge velocities that produce a louder, more characteristic sound for the same pressure differential across the pipe than older larger pipe breaches. These larger leaks can therefore be even more difficult to detect and locate, especially in portions of a distribution system that are generating a wide range of noise profiles (Lahlou, 2001). Leak noise correlators are computerized listening devices that utilize two or more highly sensitive sound detection sensors placed on each side of the suspected leak and transmit (or connect by hard-wire) to a computer that filters and calculates

a leak's location relative to the sensor array. Sound from a water loss site travels at a fixed speed which depends on the size and material of the pipe. The filtering and digital processor of the correlator is able to identify and delineate sounds typical of water breaks. Comparing the arrival times of these sounds as detected by each of the two sensors, the computer of the leak noise correlator can integrate their arrival times and thereby infer the distance that the water loss site is from the listening heads. The result of this integration is then displayed to the operator. The leak noise correlator with two fixed microphones is able to mimic the action of an operator with a single microphone moving back and forth across the water main listening for the quality and amplitude of a break sound. Faster and more accurate leak locations are possible using a correlator in the hands of a trained and experienced operator. Some leak noise correlators are wireless and provide the flexibility needed to accurately locate water loss sites along highly inaccessible routes. Table 4-10 provides more detail regarding correlators.

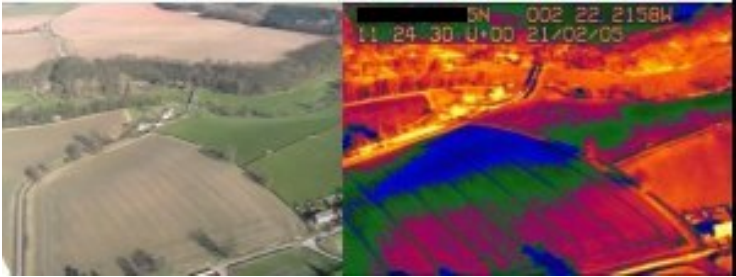
Table 4-10. Leak Noise Correlators	
Prevalent Application	Water loss detection and site location.
Strengths	<ul style="list-style-type: none"> • Accurate delineation of water loss noises from complex sonic background. • Accurate location of water loss site. • Greatly reduced time, especially along a highly inaccessible route. • Can locate leaks in PVC and DPE pipe.
Weaknesses	<ul style="list-style-type: none"> • Requires factory training. • Requires moderate care in the field.
Set-up Time	10-20 minutes.
Average on-station time	30-60 minutes but may be longer if attempting to detect during periods of high demand.
Capital Cost	\$20,000 - \$32,000 dependent on ancillary equipment (typically includes factory training).
Photo	 <p>Ref: www.utsleak.com</p>
Notes	Not unusual for the accuracy of leak locate to be better than 1m/100 meters.

4.2.4.2 Thermal Detection

Unlike acoustic devices that detect a property of the leak, thermal detection devices look for the temperature differences in the surrounding ground caused by saturation due to the leaked water.

Thermography

Thermography measures the infrared radiation (heat) emanating from the ground. Areas along a water main in which a water loss site is active will frequently exhibit saturated conditions just below the surface that may or may not be apparent on the surface. These saturated zones tend to be somewhat warmer than their surroundings in the cooler winter months. Conversely, these areas may appear cooler than their surroundings in the warmer summer months. Infrared measurement of the general area can help detect these areas of temperature differentiation and locate the water loss site. The operator can use simple hand-held infrared meters with digital temperature gauges to locate the general area to excavate for the leak. When used on a larger scale, whole-site thermography has been successful at photographing temperature variations and locating leaking below slabs, pavement and even buildings. Infrared measurement locating is most frequently used in conjunction with other methods of detection to better locate the best potential excavation sites. Table 4-11 provides more detail regarding thermography.


Table 4-11. Thermal Water Leak Detection	
Prevalent Application	Water loss site locating.
Strengths	<ul style="list-style-type: none"> • Can narrow the general area of leak site locating. • Simple to use.
Weaknesses	<ul style="list-style-type: none"> • Relies on temperature variations which may not be very large. • Gives no indication of the size of the leak. • Leaks may be masked by groundwater.
Set-up Time	5-10 minutes.
Average on-station time	15 - 30 minutes depending on ground conditions.
Capital Cost	\$150 - \$10,000 – hand-held infrared meters are fairly inexpensive but whole-site thermography can become expensive and is probably best accomplished through a knowledgeable contractor.
Photo	 <p>Visible photo on left and thermal photo on right. The water leak from the transmission main shows up as a dark blue area.</p> <p>Ref: www.thermal-imaging-survey.co.uk/archive/pipeline.htm</p>
Notes	While thermal leak detection techniques can be used for local applications, it also can be used in much larger detection areas such as for long runs of transmission mains.

4.2.4.3 Electromagnetic Detection

Various forms of electromagnetic detection devices have been developed for use in locating buried utilities, especially pipelines. Some of these same technologies are being extended to help identify leaks in these pipelines.

Ground Penetrating Radar (GPR)

GPR, also known as ground probing radar, subsurface radar, georadar, or earth sounding radar, locates and evaluates subsurface leaks without the need to expose them (Eyuboglu et al). Most GPR units operate by transmitting electromagnetic waves (125 MHz to 370 MHz) into the ground that subsequently bounce off of subsurface objects and return to the receiver head of the unit. The returned signal is processed into a picture of subsurface objects including plastic pipes, rocks and voids. Water leaking from a pipe usually can be detected and the exact location of the pipe breach can be identified real-time as the operator moves the lawn mower-sized unit along the length of, and back and forth across the pipeline. Enhanced signal processing is being developed to help the operator refine the investigation. Table 4-12 provides more detail regarding GPR.


Table 4-12. Ground Penetrating Radar	
Prevalent Application	Water loss site detection, locating and quantification.
Strengths	<ul style="list-style-type: none"> • Relatively independent of pipe material – can detect leaks in metallic, concrete and plastic pipes. • Can detect leaks in any pipe >1”. • Compact unit easily transportable. • Moderate operator training and support are required. • 3-4 m depth detection possible.
Weaknesses	<ul style="list-style-type: none"> • Requires access to route along top of pipeline. • Takes training and experience to accurately delineate leak detections. • Definition can be highly dependent on pipeline bedding and groundwater conditions.
Set-up Time	10-20 minutes, assuming site is clear of inhibiting structures or vegetation.
Average on-station time	1-3 hours depending on the length and accessibility of line to be inspected. Pipeline needs to be located and marked prior to radar scan to improve leak detection results.
Capital Cost	\$15,000 - \$31,000 depending on the size and mounting of the radar head.
Photo	 <p>Ref: www.geodetic.com.au/category1541_1.htm</p>
Notes	Only moderate operator training and support are needed to operate equipment and locate pipes but significant experience can be required for the detection of water leaks using ground-penetrating radar. While GPR quickly and accurately detects the pipeline, considerable interpretation is frequently required to see the signature of a leak.

4.2.4.4 Chemical Detection

Chemical detection techniques rely on the introduction of a detectable gas into a dewatered line or a liquid to the water. If detected outside of the pipe, it is an indication of a breach in the pipe wall. Due to the restrictions on products that can be used in conjunction with potable water supplies, these techniques must be used with forethought and great care. The local drinking water regulatory agency should be consulted before considering chemical detection.


Tracer Gas

Also called “Gas Sniffing”, is an emerging leak detection technology that was developed by the petroleum industry as a passive approach to detecting pipeline leaks. It has some applicability in the potable water sector, especially in those applications where the line can be taken out of service, dewatered and tested. The technique requires the injection of an inert gas, typically a 5% hydrogen-nitrogen mixture into a pipeline to be tested. Electro-chemical sensors are then used to detect the presence of hydrogen gas in the air just above the ground atop the tested pipeline. Once the detectors are calibrated for the ambient levels of free atmospheric hydrogen gas, they can be used to detect and locate main leak sites. In many cases the intensity of the detected hydrogen will provide indication of the size of pipeline breaches. The most frequent configuration is a hand-held detection unit (USACE, 2001). Some experimental work has been attempted using gas detection technology on operating systems. Due to the sensitivity of some waters to the nitrogen carrier gas used in this method, this technique has only limited application for some systems that must remain in operation. Table 4-13 provides more detail regarding tracer gas detection.

Table 4-13. Tracer Gas Detectors	
Prevalent Application	Water loss detection and site location.
Strengths	<ul style="list-style-type: none"> • Non-destructive testing approach. • Facilitates location of multiple leak sites. • Not dependent on pipe material, water pressure or physical shape of leak. • Can be used with either operating or dewatered lines but dewatered application results in greater sensitivity.
Weaknesses	<ul style="list-style-type: none"> • Some systems may have to be dewatered to use. • Needs careful calibration of sensors to achieve usable accuracy. • Requires extensive operator training. • Sensitivity may be somewhat weather dependent.
Set-up Time	8-12 hours depending on the dewatering and preparation time required.
Average on-station time	1-2 days depending on complexity and geometry of the section to be tested.
Capital Cost	\$16,000-\$18,000 depending on number and type of equipment attachments.
Photo	 <p>Ref: www.schoonoverinc.com/products/Leak%20Detection/leak%20detection.htm</p>
Notes	Gas detection methods are more accurate at detecting the existence of a leak in the pipeline than at locating the position of the leak due to the multiple paths that the escaped gas may take to the surface. It is very difficult to quantify the magnitude of the leak using this method. The procedure may also require disinfection and testing before the pipeline is placed back into service.

Tracer Liquids

Although infrequently used, leak detection is sometimes possible with the use of liquid tracer markers. A water system operator may be faced with having to determine if the water that is seen on the surface of the ground is coming from the public water system. Such an analysis can be facilitated by injecting a conservative (decay constant of zero) marker into the water system and then testing for this marker in the surface waters. A number of markers can be used depending on the nature of the water systems. Chlorine, although not technically considered a conservative marker, is easily injected and detected. It provides a marker for those systems that do not maintain a chlorine residual. Fluoride is another chemical that can be injected into either chlorinated or non-chlorinated system as a marker. The appearance of fluoride in the surface waters is then a positive indicator of a water loss site from the water main, although exact location and magnitude of the leak are not highly enlightened by the process. A number of manufacturers market fluorescent dyes for use in public water systems that can be injected into the distribution system and in very low concentrations are invisible to the eye in natural light, but which fluoresce under ultraviolet (blacklight) light. The dyes should be NSF Standard 60 Certified for use in a potable water system. Quantification of water loss can be attempted with fluorometer measurement of the marker dispersion of the marker. This technique is highly susceptible to interferences from the soil complex and the amount of groundwater present. Table 4-14 provides more detail regarding tracer liquid leak detection. It should be noted that addition of any tracer, including chlorine and fluoride, may be subject to state drinking water program approval.

Table 4-14. Tracer Liquid Detectors	
Prevalent Application	Water loss detection.
Strengths	<ul style="list-style-type: none"> • Can affirm the existence of a breach in the distribution system from its appearance on the surface.
Weaknesses	<ul style="list-style-type: none"> • Not very accurate method for determining location of water loss site. • Gives little information on the magnitude of the flow • Propensity for false negatives. • May not be approved for use by local health agencies.
Set-up Time	1-3 hours for preparation of field injection site.
Average on-station time	1-3 hours depending on speed that marker diffuses in line and migrates to the surface.
Capital Cost	\$100-\$300 mainly a function of the injection pump and system connection costs.
Photo	 <p>Ref: www.usabluebook.com</p>
Notes	Dye tracer studies in water systems require metering into the stream to maintain levels low enough not to be objectionable to water aesthetics but of great enough concentration to be detectable in area where leaking is suspected. More widely used in the wastewater sector.

4.2.5 LEAK LOCATING SERVICES AND OTHER POTENTIAL SOURCES FOR EQUIPMENT AND EXPERTISE

It can be expensive and it takes experience to accurately locate leaks using many of the methods described. For larger municipalities or any system planning to develop a proactive loss control and monitoring plan it makes financial sense to acquire equipment and train staff to operate it. Smaller systems might not benefit from making this capital investment and extensive commitment. There are other options available to smaller systems that might be more feasible.

It may be possible to borrow or rent the equipment from a nearby water system that has leak detection equipment or from a rental service. It may also be advantageous for a water system to contract their leak locating services to other municipalities to help offset equipment cost and staff training. For smaller systems, periodically hiring a commercial leak locating service may be the economical choice. Small water systems should talk to their primacy agency or local experts to learn of the available resources. Funding may also be available from state revolving funds or other programs for water audits.

4.2.6 PREDICTING PIPE FAILURE

While full analysis is beyond the scope of this document two important concepts should be introduced in pipe failure prediction and modeling. They are Background and Bursts Estimates (BABE) and Fixed and Variable Area Discharges (FAVAD).

BABE is a concept that was developed by Allan Lambert in 1993 for the UK National Leakage Control Initiative. It is used for calculating components of Real Losses based on the various parameters. For the analysis, real losses on different parts of the infrastructure are characterized as:

- Background leakage at joints and fittings,
- Flow rates too low for sonic detection if not visible,
- Reported leaks and bursts (high flow rates with short duration), and
- Unreported leaks and bursts (moderate flow rates with duration depending on the method of active leakage control).

BABE is a statistical model and performs better with larger samples. BABE analysis can be used for calculating components of Annual Real Losses including UARL, or components of night flows. Typical burst flow rates are specified at a standard pressure, and are adjusted to actual pressure using appropriate assumptions for Fixed and Variable Discharge path (FAVAD) N1 values. The N1 value is a calculation factor based on the piping system.

A hole or leak in a pipe has an expected leakage rate based on the size of the hole, shape of the hole, and the pressure. The Fixed and Variable Area Discharges (FAVAD) concept introduced the idea that the leak may increase or decrease with pressure due to the area of the leak changing. For instance a crack in a pipe may get wider at higher pressures and thus allow proportionally more water to escape. In the simplest versions of the FAVAD equation the Leakage Rate L (Volume/unit time) varies with Pressure N1 or $L_1/L_0 = (P_1/P_0)^{N1}$. N1 values can be calculated from tests on sectors at night. Values derived for sectors in the UK, Japan, Brazil, Cyprus, USA, Australia and New Zealand have shown that N1 generally varies between 0.50 and 1.50, with

occasional values up to 2.5. Small undetectable leaks at joints and fittings typically have N1 values around 1.50, as do larger leaks and bursts on flexible pipes. Detectable leaks and bursts on rigid pipes normally have N1 values close to 0.50.

The BABE and FAVAD concepts are used in multiple software packages that help water system managers assign values to help calculate performance indicators and prioritize pipe replacement or rehabilitation.

4.2.7 PIPE REPAIR AND REPLACEMENT

4.2.7.1 Pipe Repair Techniques and Considerations

A major center of focus of an effective water loss management program is repair/rehabilitation. Repair typically depends on trained crews, using the appropriate materials, equipped with the adequate tools to safely repair leaks quickly and securely. As expensive as repairing a leak can be, fixing it a second time can more than double the investment in labor and materials while destroying customer satisfaction.

4.2.7.2 Pipe Repair/Replacement Personnel

A trained and experienced crew that has working knowledge to conduct effective and timely leak repairs is priceless. The repair approach will depend on the leak and the environmental conditions in which the repair must be made. If the leak site is the result of small corrosion pitting or puncture holes, a repair clamp will usually work quickly and well. Leaks that result from large-hole formation or long cracks may require replacement of one or more sections of the pipe. For large steel pipe, repair may take the form of in situ welding. Repair crews need to be trained on a variety of fix approaches.

4.2.7.3 Available Equipment and Materials


It is prudent and common for utilities to maintain a small inventory of parts to support leak repairs in their distribution systems. An analysis of the leak repair history of the utility can greatly facilitate the selection of appropriate materials and quantities to stock. Many smaller operations have found that it is advantageous to reach out to neighboring water utilities that may have similar repair parts and equipment needs to be aware of what might be available in their stock in case of an emergency. Finally, for larger scale events, over 30 states have now formed mutual assistance networks called Water & Wastewater Agency Response Network (WARN) (<http://www.nationalwarn.org>) to provide expansive help between water utilities within a state and in many cases even across state lines. While WARN is primarily for disaster response, a large catastrophic failure of a major transmission line may require more resources than a PWS has available and may need assistance from a WARN partner.

4.2.7.4 Leak Repair Techniques

A variety of technologies are available to repair pipeline leaks depending on their location and size. Many studies have shown that the most significant portion of leak repair cost and time is attributed to uncovering the leak site and dewatering. From there, the repair techniques are relatively easy. For this reason, a growing portion of the leak repair market is centered on approaches that do not require that the pipeline be uncovered. The following approaches, while certainly not exhaustive, are meant to provide the user with a representation of the level of effort and potential costs that may be encountered using such techniques.


Wrapping

Some small pipe leak repairs may be made using a surface wrap depending on pipe material. Many of these products take the form of a fiberglass cloth impregnated with a resin that is activated by water. The cloth comes ready to apply and does not require any mixing or measuring. The application is largely insensitive to pipe temperature at the time of application and many brands can even be applied under water. Cracked pipes can be wrapped with the cloth and secured with a pressure sensitive rubber tape. Corrosion holes are typically patched with a two-part epoxy before being wrapped. Some products are designed for application while the pipe is under pressure, avoiding the necessity to shut-off the water service. Table 4-15 provides more detail regarding pipe wrapping.

Table 4-15. Wrapping	
Prevalent Application	Small holes and short cracks that will not tend to lengthen.
Description	<ul style="list-style-type: none"> • Cloth comes in 4", 6" and 8" widths. • Cloth rolls up to 50' long. • Can be applied to pipe under pressure (< 60 psi). • Patches rated for line service up to 300 psi.
Application Time	<ul style="list-style-type: none"> • Cure time 30 - 60 minutes before line pressure can be applied. • Total application time 1-2 hours. • Patch needs 24 hours to fully set before backfilling water main. • Typically limited to repairs on pipes 4" and under. • Product must be NSF certified in most states.
Average on-station time	Highly variable depending on site conditions: <ul style="list-style-type: none"> • Traffic conditions & traffic control needed, • Depth of pipe & availability of excavation equipment, • Depth of trench and shoring required, • Trench dewatering, • Availability of new bedding and backfill material, • System Flushing, and • Surface restoration.
Cost	\$15 - \$75 – repair kit, depending on pipe size with 2 – 4 hours repair time.
Photo	 <p>Ref: www.prime-line.net/urethane.html</p>
Notes	Works on PVC, copper, concrete, and most metals, plastic and rubber pipe materials.


Repair Clamps

Repair clamps are collars that can be fitted around the outside of the pipe to patch the hole or break. The metal collar contains a partial or full size gasket that is subsequently compressed onto the surface of the pipe by the clamp providing a pressure tight fitting to stop the leak. Table 4-16 provides more detail regarding repair clamps.

Table 4-16. Repair Clamps	
Prevalent Application	Small holes and short cracks that will not tend to lengthen.
Description	<ul style="list-style-type: none"> • Clamp usually made of stainless steel. • Clamping bolts & nuts made of stainless steel or low alloy. • Gasket material made from Styrene-Butadiene (SBR) or Nitrile (Buna-N). • Sized to match the O.D. of the pipe in lengths of 6" - 15".
Application Time	1-hour – Majority of time needed to clean, remove corrosion from the outside of the pipe and, disinfect the pipe surface in preparation for clamp placement.
Average on-station time	Highly variable depending on site conditions: <ul style="list-style-type: none"> • Traffic conditions and traffic control needed, • Depth of pipe and availability of excavation equipment, • Depth of trench and shoring required, • Trench dewatering, • Availability of new bedding and backfill material, • System Flushing, and • Surface restoration.
Cost	\$30-\$200 per clamp – depending on type and size.
Photo	 <p>Ref: www.subsurfaceleak.com</p>

Sliplining


Another approach for repairing badly leaking old water mains without having to uncover them is a process known as sliplining. In this process, the old lines are repaired by pulling a thin-walled plastic liner inside the old, cleaned pipe to seal its leaks. Sliplining leaves the old pipe intact and uses it for structural support of the much thinner plastic lining. Once the liner is in place, hot water is pumped through it, causing the liner to become malleable, expand and tightly seal onto the surface of the old pipe. In this approach, the original pipe provides the strength and structure for the pipeline while the liner provides pipeline integrity and improved system performance. Excavation is only needed at intervals along the pipe to facilitate entry and exit from the line. There is an added cost of jointing techniques when limited to using short pipe lengths. Poorly applied grouting can lead to buckling. Sliplining does not work well in pipelines with a lot of elbows and isolation valve. Table 4-17 provides more detail regarding sliplining.

Table 4-17. Sliplining	
Prevalent Application	Repair of multiple holes in pipeline without excavation.
Description	Grinding, flushing and lining of existing pipelines with thin-walled plastic linings to seal the line.
Average on-station time	Like all pipeline replacement, the on-station time is highly variable. Sliplining may require extensive carrier pipe preparation and cleaning before lining can begin. Also, connections of laterals and service connections must be made following lining. Repair times of 5-10 days per 1,000 foot of pipe to be lined can be expected.
Cost	\$120-\$135/ft installed (by commercial contractor). The price includes materials, shipment, line preparation, on-site pipe fusion, placement & thermal setting and tapping. Price does not include system dewatering, access pit excavation (350-500ft) and restoration.
Photo	 <p>Ref: www.underground solutions.com</p>
Notes	Sliplining processes require that the lining be re-tapped at all connections. Several new camera-driven and computer controlled tapping machines have greatly reduced the time this re-tapping takes.

4.2.7.5 Pipe Replacement

Open Trench Replacement


It is not unusual for a repair crew to discover that the section of leaking pipe is far too deteriorated to repair with the application of a simple repair clamp. In these cases, it may be necessary to replace one or more lengths of the pipe. While pipe repair replacements are best done using the same material as the existing pipe, lack of pipe stock or desire to upgrade to a less corrosive pipe material may dictate that the replacement length be another material. Pipe couplings and spool pieces to connect the replaced pipe section are readily available. Table 4-18 provides more detail regarding open trench pipe replacement.

Table 4-18. Replacement (Open Trench)	
Prevalent Application	Small holes and short cracks that will not tend to migrate.
Description	Replacement of one or more lengths of pipe (10', 15', 20' lengths) with new pipe.
Average on-station time	It is not unusual to expend 60%-80% of the total on-site time opening the trench, dewatering the work site, backfilling and repaving the site. The actual pipe replacement once the trench and bedding have been prepared is 2-3 hours per pipe length.
Cost	\$100-\$300 per foot of open trench – depending on pipe type, size and location.
Photo	 <p>Ref: AWWA, "Images on Tap", August 2005</p>
Notes	Flanged couplings and spool pieces may be required to connect the replacement pipe to the existing system. These ancillary pieces, sized for the specific pipe being repaired, are typically maintained by the utility as part of the emergency repair materials.

Trenchless Replacement

Aging infrastructure in water systems often means failing joints, leaking valve seals and corroded pipes, all contributing to substantial leakage from the system. A major obstacle in repairing these elements is their inaccessibility. Many water mains cannot be effectively uncovered and replaced when they are located in congested areas and critical traffic arteries. One approach to replacing these leak-ridden lines is to drag a new pipe through the older pipeline using a flexible and typically much smoother pipe material (e.g., PVC, HDPE, or Fusible C-900). The annular space between the new pipe and the old pipe should be grouted to provide added stability to the new line. If the new pipe is small enough with respect to the old pipe, some applications have used stand-offs in lieu of grouting. Although the inside diameter of the new pipeline is usually somewhat smaller than the pipe it replaced, the increased smoothness can actually result in lower headloss and, naturally, no lost water due to leaking. This technique requires a long area of space for assembly and joining of the new pipe sections. This limits the application to pipe sizes of 8 to 96 inches in diameter.

An alternative approach is to destroy the old pipe as the new one is being dragged through it. This technique can permit the same-sized or even larger diameter pipe to replace the old line. Pipe bursting can be a reasonable-cost approach to replacing long lengths of the system in areas where excavation may be difficult or impossible. A “pipe bursting” head is dragged through the existing pipeline, using it as a pathway. As the head is pulled through, it fractures the old line making room for the replacement main. The replacement pipe is attached to the bursting head and dragged into the line in one pass. Trenchless pipe replacement is most effective where long, uninterrupted runs of new pipe are needed. The approach is less cost-effective in areas where numerous fittings must be placed on the new pipe as the pipe must be exposed at each location that such an attachment is needed. Table 4-19 provides more detail regarding trenchless pipe replacement.

Table 4-19. Replacement (Trenchless)	
Prevalent Application	Complete replacement of transmission or distribution main.
Description	Fusion welded or restrained joints are required on the replacement pipeline.
Average on-station time	Highly dependent on length of pipe to be replaced, ease of opening end pits and ease of drag through line. 3-7 days are not unusual for the replacement of 1,000-ft of water main.
Cost	\$80-\$95 per foot in stalled (by commercial contractor). Highly dependent on the size of the line to be replaced, the configuration, pipe depth, and ease of opening end work pits. Pits required every 500-700 ft of line. Costs do not include cost of access pit excavation or restoration.
Photo	 <p>Ref: www.premierplumbing.biz/residential.html</p>
Notes	Due to the initial equipment investment and the specialized training that is needed to operate, trenchless pipeline replacement is frequently a proprietary process and is contracted to a specialty company by a utility.

4.2.8 SELECTING REPLACEMENT PIPE

When it is neither economically feasible nor practical to attempt a repair, wholesale replacement of the deteriorated pipe might be the practical solution. When opting to replace pipe, questions such as the following should be addressed:

- How large is the pipe?
- Has there been or will there be growth in the area requiring a larger pipe?
- Is the soil type aggressive?
- Can significant movement be expected due to poor soils or seismic activity?
- Will temporary bypass piping be necessary?
- What is the expected pressure?

- How big of a potential is there for surge?
- How much of a disruption and inconvenience will replacing the pipe be?
- Will design and/or construction be done in house or contracted?
- If a different pipe material is selected, will different equipment and training be required to repair and maintain it?

Administrators must also answer financial questions such as:

- How is the work to be financed?
- Is the replacement pipe to be a relatively short term solution or is a long service life required?

The answers to these questions will begin to determine the size and type of material that best meets the requirements. Tables 4-20 through 4-22 and Figure 4-2 are taken from *Deteriorating Buried Infrastructure Management Challenges and Strategies*, EPA (2002) and present material property criteria and comparisons for different pipe materials to illustrate the array of variables that will affect performance and costs. Figure 4-2 presents a flow chart decision process to help decide a course of action as to whether to repair or replace a pipe.

Material Property	DI	PVC	HDPE
Tensile strength	60,000 psi	7,000 psi	3,200 psi
Compressive strength	48,000 psi	9,000 psi	1,600 psi
Yield strength	42,000 psi	14,500 psi	5,000 psi
Ring bending stress	48,000 psi	none specified	none specified
Impact strength	17.5 ft-lbs/in	0.75 ft-lbs/in	3.5 ft-lbs/in
Density	441 lbs/ft ³	88.6 lbs/ft ³	59.6 lbs/ft ³
Modulus of elasticity	24,000,000 psi	400,000 psi	110,000 psi
Temperature range	< 150° F	< 140° F	-50 to 140° F under press.
Thermal expansion	0.07" per 10° F per 100'	0.33" per 10° F per 100'	1" per 10° F per 100'
Corrosion resistance (int)	Good - w/cement lining	Excellent	Excellent
Corrosion resistance (ext)	Good - w/polywrap	Excellent	Excellent
UV resistance	Excellent	Gradual strength decline	Yes - w/carbon black
Abrasion resistance	Excellent	Good	Good
Cyclic resistance	Excellent	Fair	Good
Permeation resistance	Yes	No - solvents & petroleum	No - solvents & petroleum
Scale & growth resistance	Good	Excellent	Excellent

Table 4-21. Comparison of Distribution Size Pipe Materials - Pipe Properties

Pipe Property	DI	PVC	HDPE
Trade organization	DIPRA	Uni-Bell	PPI
AWWA designation	C1 51	C900 and C905	C906
Diameter range	3" - 64"	4" - 12" (C900) 14" - 48" (C905)	4" - 63"
Pressure range	350 psi	100 psi - 200 psi	50 psi - 255 psi
ID range (8")	8.425"	7.76" - 8.33"	6.918" - 8.136"
Wall thickness range (8")	0.25"	0.362" - 0.646"	0.265" - 1.182"
Weight range (8")	21.1 lbs/ft	6.6 lbs/ft - 11.4 lbs/ft	5.1 lbs/ft - 11.06 lbs/ft
OD nominal (8")	9.05"	9.05"	9.05"
Buoyant (8" 100 psi)	No	Yes	Yes
Surge allowance	100 psi	125 - 200% of press. rating None for 14" - 48" (C905)	50 - 100% of press. rating
Surge potential (8" 100 psi)	53.6 psi per 1 ft/sec √V	17.6 psi per 1 ft/sec √V	9.8 psi per 1 ft/sec √V
Integrity under vacuum	Excellent	Good	Poor
C-factor	140	150	150
Standard pipe lengths (8")	18 ft or 20 ft	20 ft	40 ft or 50 ft
Type of joints	Push-on or mechanical	Push-on or mechanical	Heat fused
Max joint deflection (8")	5°	3°	Radius = 20 - 50 times OD
Compatible w/DI fittings	Yes	Yes	Yes - in DI sizes

Table 4-22. Comparison of Distribution Size Pipe Materials - Operational Considerations

Operational Consideration	DI	PVC	HDPE
Ease of installation	Subjective	Subjective	Subjective
Can be direct tapped	Yes	Yes	No
Need for special installation equipment	No	No	Yes
Need for special bedding for typical installations	No	Yes	No
Need for joint restraint	Yes	Yes	No
Ability to locate underground	Excellent	Poor - needs tracer wire	Poor - needs tracer wire
Applicable for above ground installations	Yes	With opaque material for UV resistance	Yes - w/proper support
Applicable for aqueous installations	Yes	Yes	Yes - but potential for flattening is high
Anticipated service life	100 years	50 - 100 years	50 years

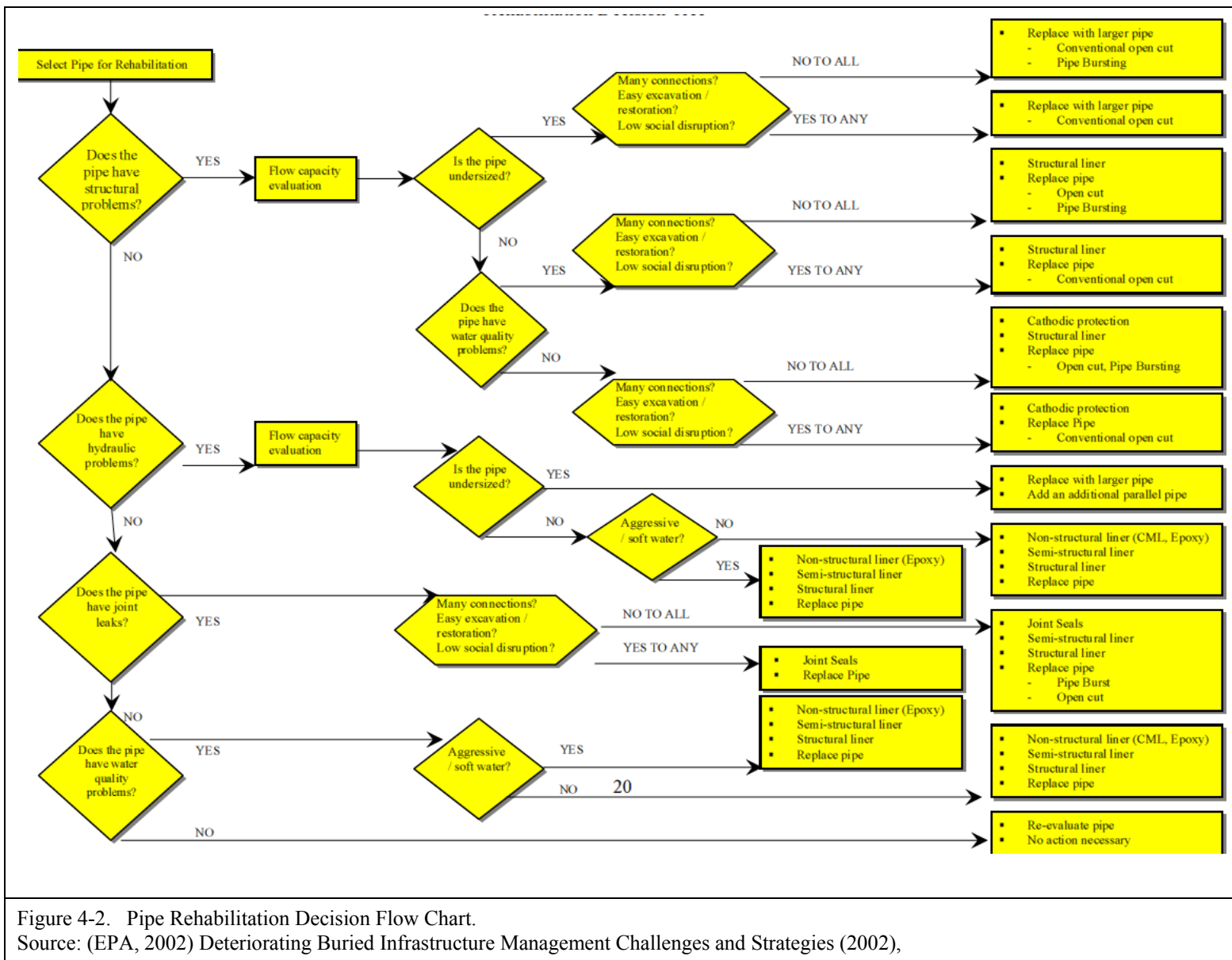


Figure 4-2. Pipe Rehabilitation Decision Flow Chart.
Source: (EPA, 2002) Deteriorating Buried Infrastructure Management Challenges and Strategies (2002),

4.2.9 OPERATION AND MAINTENANCE PROGRAMS AND PREVENTATIVE MEASURES

4.2.9.1 Effective Design and Construction

An effective water loss management program is one that incorporates water loss prevention techniques over the life cycle of the distribution system. The decision made in the design and construction phase may impact the operations of the system for years to come. There is a growing awareness within the water industry of the importance of sound asset management. Asset management is the awareness to manage all real assets throughout the life cycle of the public water system. Water loss management heavily depends on controlling the type of assets that are brought into the inventory and continuously monitoring and addressing issues as they arise.

4.2.9.2 Material Standards

The selection of material will always be driven by the economics of the project. However, heavy consideration should be placed on sustainability, durability and applicability of the materials. Material standards set by organizations such as AWWA, International Standards Organization (ISO), American Society for Testing Material (ASTM), NSF International, and American National Standards Institute (ANSI) are developed by incorporating experiences of thousands of system operators, trade organizations, manufacturers, and other agencies and organizations. For example, NSF/ANSI 61 focuses on eliminating contaminants or impurities that indirectly enter the drinking water through treatment chemicals, process media, or components of the drinking water system. These standards provide the foundation for a utility to establish its own basic standards of materials that are to be used for all system replacements and extensions. Establishing and maintaining a utility's "approved products list" helps to assure that the distribution system will be developed with materials best suited for the community.

4.2.9.3 Design Standards

Standard-setting organizations can provide invaluable service by detailing specific design approaches that can then be adopted by the utility for their work. Design standards provide the foundation to guide both the design and construction of a distribution system, which will have the greatest possibility of maintaining its integrity throughout its operating life. Due to their strength and durability, many communities use ferrous piping systems (cast iron, ductile iron, steel, etc.). The design should incorporate corrosion control in ferrous metal pipelines. Water chemistry and protective coatings can be used to protect the inside of the pipe while a wide range

of techniques (e.g., poly-wrapping, sacrificial anode placement, impressed current) are available to protect the outside of the pipe from groundwater and galvanic cell corrosive action.

4.2.9.4 Construction Control

The integrity of the distribution system must be maintained overtime to control and extend the water loss over its lifetime. The use of pipe crews with experience managing and installing water distribution systems and regular inspection throughout the process minimizes the probability of experiencing issues post-construction. The construction of a distribution system is highly complex, requiring excellence in project management, careful material acceptance, handling, storage, and exacting installation to provide a piping system which is to carry hundreds of pounds per square foot of pressure throughout its lifetime. Training can prepare in-house construction crews for construction challenges that might sneak up. Well-written and enforced contract language can go a long way toward soliciting and qualifying a contractor. Key to the process is the utility's project manager and the construction inspector. The inspector should ideally have extensive experience in pipeline construction using the materials and equipment chosen for the utility's project. The project manager should document testing of the system throughout the duration of the construction. This testing typically refers to pressure, performance and bacteriologic testing.

4.2.9.5 Effective Maintenance

An effective water loss management program should establish a maintenance program sensitive to minimizing water loss through proactive action. Once a distribution system has been properly constructed and placed in service, routine maintenance should be conducted to monitor the system's performance and identify repairs/rehabilitation as needed. Ongoing maintenance will maintain the public water system operating at optimal performance and maximize the full life expectancy of the system.

4.2.9.6 Corrosion Control

Several types of very effective corrosion control systems must be maintained if they are to continue to protect the pipe system. Impressed current systems utilize an active direct current (DC) that is impressed onto the pipeline making it cathodic and protecting it from corroding. This current (10-50 amps, 50 volt) is provided via buried electric cable from an AC/DC rectifier, receiving power from the area electrical system. The anode of the system is a buried probe that will corrode over time. Properly sized impressed current cathodic protection (ICCP) systems are highly effective at preventing corrosive leaks in the system. ICCP systems must be maintained to assure their proper and continued operation. Both the rectifiers and the anodes of these

systems must be routinely inspected. If either fails to perform, the pipeline will become unprotected and may be exposed to failure due to pipe corrosion.

Sacrificial anodes (usually magnesium) can be used for effective corrosion control. In these systems the anode bags are buried in the ground close to the pipeline and directly wired to the pipeline. The sacrificial anode will corrode more readily than the ferrous material pipeline, providing a current flow to the pipe making it cathodic and protecting it. These anode bags must be inspected routinely (most easily with a multimeter probed to the bag to measure the voltage and current flow) to assure their continued integrity. Once a bag is expended, it must be replaced.

Similar to the protection of the outside of ferrous pipelines from the corrosion due to water in contact with the pipe, the inside of the pipeline that is naturally in contact with the water may also suffer corrosion and need to be protected. Corrosion of pipes can be the result of the water quality characteristics (e.g., pH, alkalinity, biology, salts and chemicals). Corrosion is principally controlled by the pH, buffer intensity, alkalinity, and concentrations of calcium, magnesium, phosphates, and silicates in the water. Corrosion inhibitors can be added to the water as part of the normal water quality operations to reduce corrosion. These inhibitors can reduce the potential for the metal surface to be under the influence of an electrochemical potential by producing an inhibiting layer between the water and the pipe material. (CDC, 2007).

4.2.9.7 Valve Exercising & System Flushing

Well-established annual valve exercising and system flushing programs play an integral part in maintaining system integrity and reducing water loss. The principal purpose of a valve-exercise program is to assure that the valve is operable across its full range. System flushing programs are typically used to maintain water age and quality. Both of these programs can easily incorporate water loss management elements. Crews equipped with hydrophones or geophones can use the opportunity to listen to the system at the valve locations and can view the valve surrounding area for evidence of potential leaking. The valve exercising leaves a valve in a confirmed position (either fully open or fully closed). Virtually all field leak detection techniques require that the configuration of the system be known so that flows can be isolated from the portion of the system being investigated. It is common for a detection crew to believe that a valve is open (or closed) when in reality it was left in an unexpected position by others. Similarly, main flushing programs take crews to a large number of hydrants/blow-offs in the system. A crew equipped and trained to listen can often detect water running at these common system leak points.

4.2.9.8 Effective Operations and Active Pressure Management

The final element in a comprehensive water loss management program is an informed operations plan. The way that a distribution system is operated can play an effective role in reducing water loss from the system and should be given consideration when establishing a leak management program.

4.2.9.9 System Modeling

A tool growing in popularity for planning, design and operating support is the distribution system hydraulic model. PC-based hydraulic models are now affordable for even modest-sized water operations. The standard hydraulic model provides the user with an easily configurable way to understand a system's operating parameters (flow rates, pressures, water quality, age, etc.). But the heart of any hydraulic model is its calibration against field reality. Once calibrated, the model can provide the water professional a standard for how the system "should" operate. If during annual maintenance activities the system performs differently from the model's projections, a major water loss or growing minor leaking may be one culprit. Likewise, annual maintenance activities afford a perfect opportunity to recalibrate the model as needed. Integrating model routine calibration and output analysis with maintenance activities provides a potent tool for identifying and potentially even locating system losses.

4.2.9.10 Meter Assessment, Testing and Replacement Programs

Meters are key components to obtaining funds required to operate and maintain a PWS, and therefore, maintaining a meter assessment, testing and replacement program that optimizes revenue and aids in locating losses should be a priority of any operation and maintenance program. Section 3.5 discusses all of the aspects that should go into any metering program.

4.3 EVALUATION

After each water audit, the PWS manager should evaluate the data to determine where improvements can be made or where further information is required. Data gaps in the information the PWS has regarding its components and the component maintenance status should be reviewed and updated as information becomes available. After each intervention the water system manager should evaluate how successful the actions were. This may be immediately apparent, such as locating and repairing a leak, or may take significant analysis, such as evaluating whether a meter replacement program is improving customer metering results. If the goals of an action were not met, the water system manager should seek to determine why not and remedy the cause if possible.

The evaluation process reviews the results of the previous audit and the performance indicators for potential areas of improvements and signs of impending problems. Because water systems require maintenance and are always subject to deterioration, the entire process must be repeated periodically as indicated in Figure 1-2.

4.4 SUMMARY - ASSEMBLING A COMPLETE LOSS CONTROL PROGRAM

It can be overwhelming to consider all of the pieces that go into a water loss and control program if you do not already have one, although many of the pieces may already exist in your system. The following sections list the activities and components water utility managers need to consider to meet the specific demands for their systems.

4.4.1 PUTTING THE PIECES TOGETHER

Consider how your utility is going to implement the following aspects of a loss control policy answering: Who? What? When? Where? Why? How often? and How much? for each aspect.

- Record Keeping
- Audit/Balance PI and Benchmark analysis
- Economic analysis
- Metering –locating, sizing, initial installation, validation, replacement
- Meter reading or AMR
- Additional system monitoring including SCADA
- Data transfer –billing-data error analysis
- Real Loss Active Leak Detection Program
 - Periodic leak detection sweeps
 - DMA, zone flow analysis and other leak testing
 - Leak locating – method and training
 - Leak repair
 - Repair, rehabilitate, or replace analysis
 - Repair, rehabilitate, or replace design
 - Repair, rehabilitate, or replace execution

Many of the items mentioned above were only briefly described in this guidance. Larger facilities will be able to manage most of this work in house. Medium and smaller facilities will likely need help.

4.4.2 FINDING HELP

Many agencies, associations, and consortia are able to provide advice. Neighboring water systems with established programs are often willing to help smaller water systems' managers. State and Federal regulatory agencies often have programs and experts available to provide assistance. The Association of State Drinking Water Administrators (ASDWA) provides links to state drinking water and primacy agency home Web pages from their Web site at <http://www.asdwa.org> and the EPA Office of Ground Water and Drinking Water provides a Web site to assist the public and PWS operators at <http://www.epa.gov/safewater/index.html>. From this site, state drinking water information and state contacts can be also be found. The Alliance for Water Efficiency, an organization dedicated to the efficient and sustainable use of water is also a source of information and resources <http://www.allianceforwaterefficiency.org>. The Alliance serves as a North American advocate for water efficient products and programs, and provides information and assistance on water conservation efforts.

Appendix A

Summary of Selected State Water Loss Policies

Appendix A - Summary of Selected State Water Loss Policies

The following information is excerpted and summarized from
Summary of State Agency Water Loss Reporting Practices by
Janice A Beecher. (2002) The full report may be found at:
<http://www.awwa.org/Resources/Waterwiser.cfm>

Janice Beecher's *Survey of State Agency Water Loss Reporting Practices Final Report to The American Water Works Association* (2002) is the most recent and complete comparison of water loss policy by state. In this white paper, a case is argued for acceptance of water loss control standards, including reliable accounting, followed by results of a survey which describes the state of water accounting and related public state and regional policy.

Surveys were conducted with organizations and state agencies with water policy influence. A total of 37 surveys were completed, 34 from states, the rest from multi-state agencies. Policy for 11 other states was found through internet searches. This resulted in information on 46 jurisdictions, of which 43 were states. Ten issues were covered by the survey, including:

- water-loss policy,
- water-loss definitions,
- methods for accounting and reporting,
- setting standards and benchmarks,
- setting goals and targets, planning requirements,
- data compilation and publication,
- offers of technical assistance,
- giving performance incentives, and
- requiring or advising audits and enforcement if applicable.

Broadly defined, some sort of water loss policy was found in 36 jurisdictions.

A definition of water loss was given by 17 jurisdictions. It was most commonly expressed as the remaining percentage of water not recorded as billed versus water pumped into the system.

It was found that 20 state agencies and two water management districts require or provide guidelines for water accounting and/or water loss reporting.

None of the jurisdictions covered were found to impose sanctions on systems failing to meet any of the requirements. Table A-1 shows the summary of the finding for the 2002 survey. The other category in the table below represents the following agencies DRBC = Delaware River Basin Commission, SJRWMD = St. Johns River Water Management District, SWFWMD = Southwest Florida Water Management District.

Table A-1 Summary Policy Findings				
Issue	Jurisdictions	States (n = 43)	Other (n=3)	Total (n = 46)
Has some sort of Water-loss Policy Statement	AZ, CA, CT, FL, GA, HI, IN, IA, KS, KY, LA, MD, MA, MN, MD, NV, NH, NY, NC, OH, OR, PA, RI, SC, TN, TX, UT, VT, VA, WA, WV, WI, WY, DRBC, SWFWMD, SJRWMD	33	3	6
Has Formal Definition of Water Loss	AZ, CA, GA, HI, KS, MD, MA, MN, MO, OR, PA, RI, SC, TX, WI, DRBC, JRWMD	15	2	17
Accounting and Reporting	AZ, CA, GA, HI, IA, KS, KY, MD, MA, MN, MO, NY, OH, OR, PA, RI, TX, WV, WI, WY, SWFWMD, SJRWMD	20	2	22
Has Standards and Benchmarks	AZ, CA, GA, HI, IN, KS, KY, LA, MD, MA, MN, MO, NC, OH, OR, PA, RI, SC, TX, UT, WA, WV, WI, DRBC, SWFWMD, SJRWMD	23	3	26
Sets Goals and Targets	AZ, CA, FL, GA, HI, KS, KY, ME, MD, MN, MO, NM, OH, OR, PA, RI, TX, WI, SWFWMD, SJRWMD	18	2	20
Has Planning Requirements	AZ, CA, CT, FL, GA, HI, IA, KS, MD, MA, MN, MO, NV, NH, OR, PA, RI, SC, TX, VT, VA, WA, WV, WI, SWFWMD, SJRWMD, DRBC	24	3	27
Compilation and Publication by Jurisdiction	AZ, CA, HI, KS, KY, MN, PA, RI, WI, SWFWMD	9	1	10
Provides Technical Assistance	AK, CA, FL, GA, HI, KS, KY, ME, NV, ND, OR, PA, RI, SC, TN, TX, VT, WI, SWFWMD	18	1	19
Offers Performance Incentives	CA, GA, HI, IN, IA, LA, MN, NC, RI, TX, VT, SJRWMD	11	1	12
Performs Auditing and Enforcement	AZ, GA, HI, KS, MD, MN, NH, OH, OR, PA, SC, TX, WI, SWFWMD, SJRWMD	13	2	15

Table A-2 shows unaccounted for water standard for selected states

Table A-2 Selected State Standards for Unaccounted-for Water		
<i>State</i>	<i>Agency</i>	<i>Standard</i>
Arizona	Department of Water Resources	10% (large) 15% (small)
California	Urban Water Conservation Council	10%
Florida	Southwest Florida Water Management District	12% or less
Florida	St. Johns River Water Management District	10%
Georgia	Environmental Protection Division	Less than 10%
Indiana	Department of Environmental Management	10 to 20%
Kansas	Kansas Water Office	15%
Kentucky	Department of Energy, Water and Sewer Branch	15%
Louisiana	Department of Environmental Quality	15%
Massachusetts	Department of Environmental Protection	15%
Minnesota	Department of Natural Resources	10%
Missouri	Department of Natural Resources	10%
North Carolina	Division of Water Resources	15%
Ohio	Public Utility Commission and Environmental Protection Agency	15%
Oregon	Water Resources Division	10-15%
Pennsylvania	Public Utility Commission	20%
Pennsylvania	Bureau of Water and Wastewater Management	10-15%
Rhode Island	Water Resources Board	10-15%
South Carolina	Public Service Commission	7.5%
South Carolina	Department of Health and Environmental Control	10%
Texas	Water Development Board	10 to 15%
Texas	Natural Resources Conservation Commission	20%
Washington	Department of Health	20% (10% proposed)
West Virginia	Public Service Commission	15%
Wisconsin	Public Service Commission	15% (large) 25% (small)
Delaware River Basin Commission	Delaware River Basin Commission	15%

Appendix B

Miscellaneous Data

Appendix B - Miscellaneous Data

Table B-1 Estimated per/Capita/Day Water Use by State						
State	Abbrev.	Gal/ Day/ Capita		State	Abbrev.	Gal/ Day/ Capita
Alabama	AL	100		Nebraska	NE	115
Alaska	AK	79		Nevada	NV	213
Arizona	AZ	150		New Hampshire	NH	71
Arkansas	AR	106		New Jersey	NJ	75
California	CA	147		New Mexico	NM	135
Colorado	CO	145		New York	NY	119
Connecticut	CT	70		North Carolina	NC	67
Delaware	DE	78		North Dakota	ND	86
Dist. Of Columbia	DC	179		Ohio	OH	50
Florida	FL	111		Oklahoma	OK	85
Georgia	GA	115		Oregon	OR	111
Hawaii	HI	119		Pennsylvania	PA	62
Idaho	ID	186		Puerto Rico	PR	67
Illinois	IL	90		Rhode Island	RI	76
Indiana	IN	76		South Carolina	SC	81
Iowa	IA	66		South Dakota	SD	85
Kansas	KS	86		Tennessee	TN	143
Kentucky	KY	70		Texas	TX	218
Louisiana	LA	124		Utah	UT	80
Maine	ME	58		Vermont	VT	75
Maryland	MD	105		Virginia	VA	138
Massachusetts	MA	66		Washington	WA	74
Michigan	MI	77		West Virginia	WV	52
Minnesota	MN	148		Wisconsin	WI	163
Mississippi	MS	123		Wyoming	WY	48
Missouri	MO	86	Virgin Islands	VI	23	
Montana	MT	129	United States Avg.		105	
Source: Soley et al. Water Distribution System Handbook, Larry W Mays.2000 Pub. McGraw-Hill						

Table B-2 Snapshot of high water loss within distribution systems							
Name	State	Volume Input (MG/Year)	Water Losses (MG/Year)	Loss Percentage	Population Served	Per Capita Loss in Gallons/Year	Value of Losses (2008 Yr USD)
Philadelphia Water Department	PA	97,637	30,448	31.18%	1,670,000	58,465	\$32,272,301
Cleveland Division of Water	OH	94,000	27,000	28.72%	1,500,000	62,667	\$28,617,713
Memphis Light, Gas & Water	TN	54,798	8,330	15.20%	908,222	60,335	\$8,829,094
Cincinnati Water Works	OH	47,047	8,303	17.65%	900,000	52,274	\$8,800,477
Jefferson Parish Water Department	LA	25,098	6,055	24.12%	425,108	59,039	\$6,417,787
Portland Water District	ME	9,293	1,678	18.06%	190,000	48,911	\$1,778,538
Ann Arbor Utilities Department	MI	6,222	1,604	25.78%	163,500	38,055	\$1,700,104
Duluth/ Public Works & Utilities/ Water	MN	8,774	1,424	16.23%	99,600	88,092	\$1,509,319
North Penn Water Authority	PA	3,311	538	16.25%	80,000	41,388	\$570,234
Waterloo Water Works	IA	5,212	812	15.58%	75,000	69,493	\$860,651
Lorain Utilities Department	OH	4,250	850	20.00%	74,000	57,432	\$900,928
Madison County Water Department	AL	2,326	623	26.77%	67,200	34,613	\$660,327
Elmira Water Board	NY	2,509	634	25.27%	65,000	38,600	\$671,986
Lebanon Authority	PA	2,371	500	21.08%	57,000	41,596	\$529,958
Selmer Utility Division	TN	800	200	25.00%	55,000	14,545	\$211,983
Renton	WA	2,666	498	18.66%	51,140	52,131	\$527,838
Williamsport Municipal Water Authority	PA	2,610	917	35.13%	51,000	51,176	\$971,942
Albany	OR	3,163	788	24.91%	41,000	77,146	\$835,213
Eastpointe Water and Sewer	MI	1,386	359	25.88%	34,077	40,673	\$380,510
Lake County East Utilities	OH	1,394	219	15.72%	26,650	52,308	\$232,121
Paradise Irrigation District	CA	2,801	464	16.57%	26,000	107,731	\$491,801

Table B-2 Snapshot of high water loss within distribution systems							
Name	State	Volume Input (MG/Year)	Water Losses (MG/Year)	Loss Percentage	Population Served	Per Capita Loss in Gallons/Year	Value of Losses (2008 Yr USD)
Cordele	GA	4,911	746	15.19%	21,600	227,361	\$790,697
Shoshone Municipal Pipeline	WY	4,911	746	15.19%	21,600	227,361	\$790,697
Piqua Municipal Water System	OH	721	152	21.10%	20,500	35,171	\$161,107
Fredericksburg	VA	1,460	365	25.00%	20,000	73,000	\$386,869
Clearfield Municipal Authority	PA	487	115	23.61%	17,000	28,647	\$121,890
Bellingham DPW	MA	598	140	23.43%	15,000	39,867	\$148,388
Miami Utility Dept.	OK	788	210	26.61%	14,500	54,345	\$222,582
Glens Falls Water Department	NY	1,364	334	24.48%	13,000	104,923	\$354,012
City of Converse-Public Works	TX	501	150	29.85%	11,508	43,535	\$158,987
Spencer Municipal Utilities	IA	585	93	15.90%	11,500	50,870	\$98,572
Anson County Water System	NC	2,467	614	24.87%	11,200	220,268	\$650,788
Berea College Utilities	KY	851	154	18.10%	11,000	77,364	\$163,227
Crossett Water Commission	AR	512	85	16.52%	9,000	56,889	\$90,093
Warren County Utility District	TN	600	100	16.67%	7,200	83,333	\$105,992

Source: AWWA, 2003

* Greater than 15% total water loss, of which more than 50% was real loss.

Appendix C

Water Audit Worksheet Examples

Appendix C - Water Audit Worksheet Example

From:

Texas Water Development Board - Water Audit Worksheets

TWDB (Texas Water Development Board) and Mark Mathis. 2005. *Water Loss Manual*. Austin, Texas: Texas Water Development Board.

http://www.twdb.state.tx.us/assistance/conservation/Municipal/Water_Audit/Leak_Detection/WaterLossManual_2005.pdf

WATER AUDIT WORKSHEET

Utility Name: _____

Type of Utility: (circle one) WSC MUD WCID SUD CITY Other _____

Regional Water Planning Group(s) in which this system operates: _____
http://www.twdb.state.tx.us/mapping/maps/pdf/sb1_groups_8x11.pdf

Name of person completing this form: _____

Phone number of person completing form (with area code) _____

Mailing address of utility: _____

Reporting Period: From _____ To _____

Percentage of water used: Surface _____ Groundwater _____

Mean household income of population served: _____
<http://factfinder.census.gov/servlet/SAFFPeople?>

Population served: _____

Note: unit of measure (acre-foot or million gallons) must stay consistent throughout report

1. SYSTEM INPUT VOLUME **MG** **ACRE-FT** **OTHER** _____

System Input Volume - Amount of water put into delivery system: _____

Master Meter Adjustment - Volume master meter did not account for: +/- _____

Corrected Input Volume - Water delivery plus/minus Master Meter Adjustment: _____

2. AUTHORIZED CONSUMPTION

Revenue Water

Billed Metered - All water sold: _____

Billed Unmetered - All water sold but not metered: _____

Non-Revenue Water

Unbilled metered - City and local government use, metered line flushing: _____

Unbilled unmetered - Line flushing/fire dept use: (estimate) _____

Authorized Consumption - The total of all Authorized water: _____

3. WATER LOSS

Apparent Loss

Customer Meter Under-Registering – Inaccurate customer meters +/-

Billing Adjustment/Waivers

Unauthorized consumption (theft or estimate)

Total of Apparent Loss

Real Loss

Storage tank overflows (estimate)

Main break/leaks: (estimate)

Customer service line leaks/breaks: (estimate)

Total of Real Loss

Total Water Loss = Apparent Loss + Real Loss

4. TECHNICAL PERFORMANCE INDICATORS

Performance Indicators for Real Loss

Number of service connections

Number of miles of main lines

Service connections divided by miles of main

Total Real Loss/Miles of Main/365

Total Real Loss/No. of Service Connections/365

5. FINANCIAL PERFORMANCE INDICATORS

Total Real Loss

Production cost of water

Total Real Loss multiplied by production cost of water:
(Example from instruction sheet) Real Loss x \$2.50/1000

Total Apparent Loss

Retail cost of water

Total Apparent Loss multiplied by retail cost of water:
(Example from instruction sheet) Apparent Loss x \$4.25/1000

WATER AUDIT WORKSHEET INSTRUCTIONS

This instruction guide is designed to aid in completing the Water Audit Reporting Form and submitting the most accurate data available. This information will aid in determining which operational areas may need assistance. A few general notes on the first section:

- List the Regional Water Planning Group in which the utility is located. This information may be determined by using the Web site listed on the reporting form.
- Remember that the type(s) of source water used must total 100%.
- Use the Web address on the reporting form to locate the mean income of population served. The data may be obtained by metropolitan area, county, and/or zip code.
- Estimate the population the utility serves (this is not the number of service connections).
- Note the reporting period. Either a calendar or fiscal year may be used.
- Use consistent units in reporting the data, either million gallons or acre-feet.

1. System Input Volume

a. Water Delivery – Includes all water pumped, produced, or obtained through interconnects and purchased water. This is the sum of all master or source meters for the year.

Example:

Water Delivery is 8,983,674 gallons

b. Master Meter Accuracy - Is achieved by calibrating the master or source meters to determine the accuracy level expressed as a percentage.

Example:

Water Meter Accuracy is 96%.

c. Corrected Input Volume- Is obtained by dividing the Water Delivery by Water Meter Accuracy and multiplying by 100.

Example:

$$8,983,674 \div .96 = 9,357,993$$

d. Master meter adjustment - Is obtained by subtracting Water Delivery from the Corrected input volume.

Example:

$$9,357,993 - 8,983,674 = 374,319$$

Note: If meters are over registering, divide Water Delivery by 1.03, if the meters are 103 percent accurate and subtract the adjustment due to the over registering of the meter. The master meters have registered more water than the actual pumped amount.

2. Authorized Consumption

- a. **Billed Metered** – All water sold that has been metered.
- b. **Billed Unmetered** – All water sold but not metered; can be an estimate.
- c. **Unbilled Metered** – Unbilled water but is metered. Enter all metered flushing here.
- d. **Unbilled Unmetered** – Unbilled water that is not metered. Enter all unmetered flushing here.

Note: Authorized Water Usage may be subtracted from the Corrected Input Volume to obtain Total Water Loss for the year.

$$\text{Corrected Input Volume} - \text{Authorized Water Usage} = \text{Total Water Loss}$$

3. Water Loss

A. Apparent Loss

- a. **Customer Meter Under Registering** – If customer meters are 98% accurate, that means the meters are 2% under registering. **Simply divide the Total Water Sold by accuracy level of meters.**

Example:

Total Water Sold that has been metered = 7,125,000 million gallons

$$7,125,000 \div .98 = 7,270,408 \text{ gallons}$$

$$7,270,408 - 7,125,000 = 145,408 \text{ gallons not recorded by meter.}$$

Note: If meters are over registering by 4 % then divide Water Delivery by 1.04 and then subtract that amount.

- b. **Billing Adjustments/Waivers** – Amount of water that was waived during the audit year.

Example:

If the utility waived 28,000 gallons due to leaks on the customer's side during the year, 28,000 would be entered.

- c. **Unauthorized Consumption** – Estimate amount of water lost due to theft.

Example: If a customer moved into a new home and began to use water without authorization.

B. Real Loss

- a. **Tank Overflows** - Amount of water lost due to storage overflows.
- b. **Main Leaks/Breaks** – Amount of water lost through main leaks and breaks.
- c. **Customer Service line Leaks** – Amount of water lost through service line leaks.

Real Loss estimates should be as accurate as possible.

Note: The sum of Total Water Loss and Authorized Consumption equals Corrected Input Volume.

4. Technical Performance Indicators

Performance Indicators are quantitative measures of key aspects within the utility. With the use of these indicators, each utility will have a history to track performance.

The first formula is Total Real Loss/Miles of Main/Day:

1. Use the Total Real Loss number from the reporting form, then divide by
2. Miles of Main lines, then divide by
3. 365 (days in a year)
4. Record this number where indicated.

The second formula is Total Real Loss/No. of Service Connections/Day:

1. Use the Total Real Loss number from the reporting form, divide by
2. Number of Service connections, divide by
3. 365 (days in a year)
4. Record this number where indicated.

5. Financial Performance Indicators

1. Value of Current Real Loss

Example

Total of Real Loss = 1,625,394 gallons

\$2.50/1000 = production cost

$$1,625,394 \times \$2.50/1000 = \$4,063.50$$

\$4,063.50 (Value of Real Loss /year)

2. Value of Current Apparent Loss

Example

Total of Current Loss = 189,408 gallons

\$4.25/1000 = retail rate

$$189,408 \times 4.25/1000 = \$805.00$$

\$805.00 (Value of Current Apparent Loss/year)

Appendix D

CUPSS Example



Appendix D

Check Up Program for Small Systems (CUPSS)



Credits, debits, new equipment, old equipment, repairs, upgrades...it is a lot to keep straight. The U.S. Environmental Protection Agency (EPA) has created a tool to help water systems keep all aspects of asset management straight: the Check Up Program for Small Systems (CUPSS). CUPSS is a free software package that has a downloadable, detailed user manual to help water and wastewater systems use the software to best help them.

What is CUPSS?

CUPSS is a simple, easy to use asset management program that helps small utilities manage and finance existing and future drinking water and wastewater infrastructure. CUPSS is stand-alone, user-friendly software with an attractive interface and tutorial, delivered on CD. The end-user for CUPSS is a small public water system or wastewater facility serving less than 3,300 customers or medium-sized systems new to asset management. The program offers personalized, intuitive navigation, including areas like “My Check Up Reports” and “My CUPSS Plan.”

Why use CUPSS?

CUPSS can assist in water loss management. Operation and maintenance schedules can be entered, including daily, weekly, monthly and yearly tasks. A user could set-up tasks to monitor loss and the regular maintenance of assets. The software allows for the task to be assigned to specified day(s) and time(s). It also helps create a schematic of a system and an inventory of its equipment. Small icons can be linked to show pumps, distribution lines, chemical systems, wells, and other parts of a system and how they work together.

The schematic can be created along with an inventory list. CUPSS serves as an asset inventory database. When creating the inventory, the software asks for the condition and age of each item. The cost, maintenance schedule and supplier and/or manufacturer can be added for each inventory item. Also, a notes field is available to add any additional information a user wants to note for the asset.

CUPSS provides Check Up and CUPSS Plan reports. The Asset Check Up report tool provides a report of assets entered and their risks. The Financial Check Up Report tool projects a 10 year financial status. My CUPSS Plan tool creates a customized asset management plan. This comprehensive feature draws information entered throughout CUPSS and formats the information into a user-friendly report.

Where do I find CUPSS?

Basic information about CUPSS, software download and training materials may be found at epa.gov/cupss.

Selected Screen Captures from the CUPSS Software Program

Check Up Program for Small Systems (CUPSS)

Set-up | Switch Utility | Create User | Help | Training | Exit

My Home | My Inventory | My O & M | My Finances | My Check Up | My CUPSS Plan

Beauty View Acres Subdivision - DW [Print Blank Worksheet](#)

The asset inventory form allows you to enter information about your assets. This information will then be used in several of the CUPSS reports and to generate your prioritized asset list. **(*) Indicates required fields**

Basic Information

* Asset Name ? Select Associated Asset ?
 * Location ? Select Associated Location ? [Add]
 * Asset Category ? * Asset Type ?
 ID ? Size ?
 Latitude ? Longitude ?
 Notes ?

Status and Condition - Required to Calculate Priority

* Condition ? * CoF ?
 * Redundancy ? Can this asset be repaired? ☐ Yes ☒ No ?
 * Asset Status ? Can this asset be rehabilitated? ☐ Yes ☒ No ?
 Select Asset ? Show asset in the schematic? ☐ Yes ☒ No

Asset Risk Matrix

Consequence of Failure

Low Risk High Risk

Probability of Failure

Inventoried Asset List

- Source
 - Well#1
 - pump
 - well property
 - Wellhouse Tampa
- Pumping Facility
 - Main valve
 - Security
 - Chlorinator
 - Well House
- Treatment
 - Chlorine testing
- Storage
 - Storage Tank
- Distribution

Figure D-1. Asset Inventory window. The Asset Inventory window has 4 parts: (1) Basic Information, (2) Status and Condition, (3) Cost and Maintenance and (4) Manufacturer and Supplier. This figure shows the first 2 parts.

Status and Condition - Required to Calculate Priority			
* Condition	Select Condition Rating	* CoF	Select CoF Rating
* Redundancy	Select Redundancy	Can this asset be repaired?	<input type="radio"/> Yes <input checked="" type="radio"/> No
* Asset Status	Select Status	Can this asset be rehabilitated?	<input type="radio"/> Yes <input checked="" type="radio"/> No
Select Asset Replaced	Select Asset Being Replaced	Show asset in the schematic?	<input type="radio"/> Yes <input checked="" type="radio"/> No

Cost and Maintenance			
* Installation Date		Original Cost	
* Expected Useful Life		* Replacement Cost	
		Routine Maintenance Cost	Select Frequency
<input type="checkbox"/> Maintained According to Factory Recommendation			Create a task

Manufacturer and Supplier - Optional			
Model Number		Supplier	Select Existing Supplier
		Manufacturer	Select Existing Manufacturer
Address			
City, State, Zip		Select state	
Phone, Fax			

Figure D-2. Asset Inventory window continued. The Asset Inventory window has 4 parts: (1) Basic Information, (2) Status and Condition, (3) Cost and Maintenance and (4) Manufacturer and Supplier. This figure shows the 3 of the 4 parts.

Check Up Program for Small Systems (CUPSS)

Check Up Program for Small Systems Set-up | Switch Utility | Create User | Help | Training | Exit

My Home My Inventory My O & M My Finances My Check Up My CUPSS Plan

Beauty View Acres Subdivision - DW Inventory

The following is a list of assets currently in your inventory. To sort the table click on the column headings. To edit the information, right click on the selected record and click "edit row".

Priority	Asset	Category	AssetType	Condition	CoF	Redundancy	Replacement Date
1	Well#1	Source	Wells and Springs	Poor	Catastrophic	0%	2009-02-01
2	pump	Source	Pumping Equip...	Good	Catastrophic	0%	2011-02-01
3	Main valve	Pumping Facility	Pumping Equip...	Fair (Average)	Major	0%	2011-02-01
4	Security	Pumping Facility	Security Equipm...	Good	Minor	0%	2009-02-01
5	Tank	Distribution	Distribution / C...	Good	Catastrophic	0%	2036-02-01
6	Chlorinator	Pumping Facility	Disinfection Equ...	Fair (Average)	Insignificant	0%	2008-02-01
7	Distribution	Distribution	Distribution / C...	Good	Major	0%	2038-02-01
8	Water Producti...	Distribution	Distribution / C...	Fair (Average)	Minor	0%	2035-02-01
9	Chlorine testing	Treatment	Lab / Monitorin...	Excellent	Insignificant	100%	2008-02-01
10	well property	Source	Land	Excellent	Insignificant	0%	2308-02-01
11	Storage Tank	Storage	Concrete & Met...	Good	Moderate	0%	2055-02-01
12	Well House	Pumping Facility	Pumping Equip...	Good	Major	0%	2019-02-01
Not Available	Wellhouse Tampa	Source	Wellhouse	None	None	None	None

<< Return

Figure D-3. My Inventory List. On this page, you can see a list of all saved assets. Each asset is given a priority based on the information entered in the Asset Inventory form.

Appendix E

Case Studies of Implemented Water Loss Programs

Appendix E - Case Studies of Implemented Water Loss Programs

(EPA is currently searching for case studies of smaller water systems that have implemented a water loss prevention program.)

References

References

- Achim, D., F. Ghotb, K.J. McManus. 2007. Prediction of water pipe asset life using neural networks. J. Infrastruct. Syst. Vol. 13(1):26-30.
<http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=JITSE4000013000001000026000001&idtype=cvips&gifs=yes> (accessed 3-Sep-08).
- Adixen-USA. Liquid and gas transportation; Commissioning and maintenance. Alcatel Vacuum Technology.
<http://www.adixen-usa.com/all/dyn/markets/application.php?pid=94&div=2&lg=us> (accessed 2-Sep-08).
- American Society of Civil Engineers (ASCE). 2005 Report Card on America's Infrastructure.
http://www.asce.org/files/pdf/reportcard/2005_Report_Card-Full_Report.pdf (accessed 2-Sep-08)
- Andersen, Bjørn, and Per-Gaute Pettersen. 1996. The benchmarking handbook: Step-by-step instructions. New York, NY: Springer.
- Arcsott, A. International Water Association, Water Loss Conference 2007.
http://www.waterloss2007.com/pdf_vortraege/Mittwoch/C9-3.pdf (accessed Sep-08)
- ASI (Acoustic Systems Incorporated). Leak detection system overview. Houston, Texas: ASI.
<http://www.wavealert.com/Pages/sys1.html> (accessed 3-Sep-08).
- AWWA (American Water Works Association). 1999. Water audits and leak detection, 2nd Ed. (Manual of Water Supply Practice M-36). Christensen, Melissa, and Michael Malgrande, eds. Denver, CO: American Water Works Association.
- AWWA (American Water Works Association). 2003. WATER:\STATS, 2002 water utility distribution database. Denver, CO: AWWA.
- AWWA (American Water Works Association). 2008. Free water audit software. Denver, CO: AWWA.
<http://www.awwa.org/Resources/Content.cfm?ItemNumber=590> (accessed 3-Sep-08).
- AWWA (American Water Works Association). 2008. Water loss control. Denver, CO: AWWA.
<http://www.awwa.org/Resources/topicspecific.cfm?ItemNumber=3653&navItemNumber=3297> (accessed 3-Sep-08).
- AWWA (American Water Works Association). More water for your dollar-arriving at an economic level of water loss. Denver, CO: AWWA.
http://www.awwa.org/files/resources/waterwiser/references/pdfs/GENERAL_WATER_LOSS_MWH_Arriving_at_an_Economic_Level_of_Water_Loss.pdf (accessed 3-Sep-08).
- AwwaRF (American Water Works Association Research Foundation). 2008. AwwaRF featured topics - Key findings. Denver, Colorado: AwwaRF.

<http://www.awwarf.org/research/TopicsAndProjects/keyFindings.aspx?id=99> (accessed 2-Sep-08).

Baltzley, Steve. Water meter testing. Avanticompany.com. Avon Park, FL: Avanti Company. <http://www.avanticompany.com/articles/metertesting.html> (accessed 3-Sep-08).

Beecher, Janice A. 2002. Survey of state agency water loss reporting practices. Indianapolis, IN: Beecher Policy Research, Inc. <http://www.cuwcc.org/Uploads/committee/AWWAWaterLossPolicySurvey.pdf> (Accessed 29-Aug-08).

Besner, M.-C., V. Gauthier, P. Servais, and A. Camper. 2002. Explaining the occurrence of coliforms in distribution systems. Jour. AWWA 94(8):95-109.

Bonds, Richard W., P.E. 1997. Stray current effects on ductile iron pipe. Birmingham, AL: Ductile Iron Pipe Research Association.

Boorman, G. A. V. Dellarco, J. K. Dunnick, R. E. Chapin, Sid. Hunter, F. Hauchman, H. Gardner, M. Cox, and R. C. Sills. 1999. Drinking Water Disinfection Byproducts: Review and Approach to Toxicity Evaluation. Environmental Health Perspectives, Vol. 107, Supplement February 1999. pp 207-217. <http://www.pubmedcentral.nih.gov/picrender.fcgi?artid=1566350&blobtype=pdf>

Bourg, Joseph. 2008. Water conservation. WBDG (Whole Building Design Guide), National Institute of Building Sciences. http://www.wbdg.org/resources/water_conservation.php (accessed 3-Sep-08).

Brady, Jr., Robert F. 1995. Fact sheet from the Navy pollution prevention conference on the restoration of drinking water piping with nontoxic epoxy linings. 1995 Navy Pollution Prevention Conference, Arlington, VA, June 6, 1995. <http://www.p2pays.org/ref/11/10365.htm> (accessed 3-Sep-08).

Brothers, Ken. 2003. A practical approach to water loss reduction. IWA Water Loss Task Force. London, UK: IWA Publishing. <http://www.iwapublishing.com/pdf/WaterLoss-Jun.pdf> (accessed 3-Sep-08).

Burstall, Tim. 1997. Bulk water pipelines. London, UK: Thomas Telford.

Business Wire. 2005. American water announces pilot program in water loss management; Connellsville, PA pilot uses AMR technology to detect and repair leaks. Findarticles.com, July 15, 2005. http://findarticles.com/p/articles/mi_m0EIN/is_2005_July_15/ai_n14790673/pg_1 (accessed 3-Sep-08).

Buyer's Inspection Service. Polybutylene piping. Dayton, OH: Buyer's Inspection Service. <http://www.greatinspector.com/faq-plum-poly.html> (accessed 2-Sep-08).

Camper, A. K., K. Brastrup, A. Sandvig, J. Clement, C. Spencer, and A. J. Capuzzi. 2003. Effect of distribution system materials on bacterial regrowth. Jour.AWWA 95(7):107-121.

Centers for Disease Control and Prevention, Division of Oral Health, (CDC) August 16, 2007. Fluoridation of Drinking Water and Corrosion of Pipes in Distribution Systems, Fact Sheets, http://www.cdc.gov/Fluoridation/fact_sheets/engineering/corrosion.htm (accessed 2-Sep-08).

Chase, Bruce W., and Laura B. Triggs. 2001. How to implement GASB Statement No. 34. Journal of Accountancy Online 192(5), November, 2001. <http://aicpa.org/pubs/jofa/nov2001/chase.htm> 3-Sep-08 (accessed 3-Sep-08).

Chemical Injection Technologies, Inc. 2007. WG-602 Water Quality Analyzer. Fort Pierce, FL: Chemical Injection Technologies, Inc. <http://www.chlorinators.com/PDFs/Brochures/WG-602SellSheet.pdf> (accessed 2-Sep-08).

City of Minneapolis, Public Works. Water meter questions. City of Minneapolis, Minnesota. <http://www.ci.minneapolis.mn.us/utility-billing/watermeter.asp> (accessed 2-Sep-08).

Committee on Public Water Supply Distribution Systems: Assessing and Reducing Risks. 2006. Drinking water distribution systems: assessing and reducing risks. Washington, DC: The National Academies Press. http://www.nap.edu/catalog.php?record_id=11728

Corbitt, Robert A. 1990. Standard handbook of environmental engineering. New York, NY: McGraw-Hill.

Craun, M. F., Gunther F Craun , Rebecca Calderon and Michael J. Beach. 2006. Waterborne Outbreaks reported in the United States, Jor. Of Water and Health 04.Suppl 2, pp 19-30. http://epa.gov/nheerl/articles/2006/waterborne_disease/waterborne_outbreaks.pdf

Craun, G. F., and R. L. Calderon. 2003. Waterborne disease outbreaks caused by distribution system deficiencies. Jour. AWWA 93(9):64-75.

Cromwell, J., E. Speranza, and H. Reynolds. 2001a Reinvesting in Drinking Water Infrastructure: Dawn of the Replacement Era. Denver, CO: AWWA.

Cromwell, J., G. Nestel, R. Albani, L. Paralez, A. Deb, and F. Grablutz. 2001b. Financial and Economic Optimization of Water Main Replacement Programs. Denver, CO: AWWA Research Foundation.

CUWCC (California Urban Water Conservation Council). 2005. Data and methods for cost-effectiveness analysis. Sacramento, CA: CUWCC. http://www.cuwcc.org/uploads/tech_docs/Costs_Savings_Study_Final_042805.pdf (accessed 3-Sep-08).

CUWCC (California Urban Water Conservation Council). 2007. BPM cost and savings study. Sacramento, CA: CUWCC. <http://www.cuwcc.org/technical/bmp03/BMP03-Excerpt-Costs-Saving-Study-v6-July-2007.pdf> (accessed 3-Sep-08).

Deb, A.K., Y.J. Hasit, H.M. Schoser, and J.K. Snyder. 2002a. Decision Support System for Distribution System Piping Renewal. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., F.M. Grablutz, Y.J. Hasit, J.K. Snyder, G.V. Loganathan, and N. Agbenowski. 2002b. Prioritizing Water Main Replacement and Rehabilitation. Denver, CO: AWWA Research Foundation.

deMonsabert, S., and B.L. Liner. 1996. WATERGY: A water and energy conservation model for federal facilities. Paper presented at CONSERV '96, January 6, 1996, in Orlando, Florida. http://www1.eere.energy.gov/femp/pdfs/watergy_manual.pdf (Accessed 29-Aug-08).

Dickinson, Mary Ann. 2008. A vision for advanced water conservation. Alliance for Water Efficiency. http://www.texaswatermatters.org/pdfs/Mary_Ann_part1.pdf (accessed 2-Sep-08).

Dickinson, Mary Ann. 2008. Developing water conservation strategies. Alliance for Water Efficiency. <http://www.co.mchenry.il.us/common/countyDpt/WaterRes/PDFDocs/08-05-13McHenryCountymaryannandickinson.pdf> (accessed 2-Sep-08).

DIPRA (Ductile Iron Pipe Research Association). 2007. Ductile iron pipe joints and their uses. Birmingham, Alabama: DIPRA. <http://www.dipra.org/pdf/joints.pdf> (accessed 2-Sep-08).

DOH (Washington State Department of Health). 2007. Water use efficiency handbook. Washington State Department of Health, Division of Environmental Health, Office of Drinking Water, DOH Pub. # 331-375. http://www.doh.wa.gov/ehp/dw/municipal_water/331-375_7-24-07.pdf (accessed 3-Sep-08).

DWR (State of California Department of Water Resources). 2008. Urban drought guidebook. State of California Department of Water Resources Office of Water Use Efficiency and Transfers. <http://www.owue.water.ca.gov/docs/UrbanDroughtGuide.pdf> (accessed 2-Sep-08).

EBAA Iron Connections, GI-1, 1993. Corrosion & Cathodic Protection in Underground Piping Systems", <http://www.ebaa.com/pdf/pdf/GI-1.pdf> (accessed 2-Sep-08).

Elert, G., and his students. 2004. Price of water. In The Physics Factbook, Glenn Elert, ed. Hypertextbook.com. <http://hypertextbook.com/facts/2004/JosephSabatelle.shtml> (accessed 3-Sep-08).

EOEA (Executive Office of Environmental Affairs) and WRC (Water Resources Commission). 2006. Water Conservation Standards. The Commonwealth of Massachusetts. http://www.mass.gov/envir/mwrc/pdf/Conservation_Standards.pdf (Accessed 15-Aug-2008).

EPD (Georgia Environmental Protection Division). 2007. Water loss control program: EPD guidance document. Georgia Environmental Protection Division, Watershed Protection Branch. http://www1.gadnr.org/cws/Documents/Water_Loss_Program.pdf (accessed 3-Sep-08).

European Pipeline Center. Clean water service. St Veit an der Glan, Austria: MTA Messtechnik. http://www.mta-messtechnik.at/GB/trinkwasser2_GB.html (accessed 3-Sep-08).

Eyuboglu, S., Mahdi, H., and Al-Shukri, H., Dept of Applied Science, University of Arkansas. Detection of Water Leaks Using Ground Penetrating Radar, <http://www.dot.state.fl.us/statematerialsoffice/geotechnical/conference/materials/eyuboglu-mahdi-alshukri.pdf> (accessed 2-Sep-08)

Fantozzi, M., and A. Lambert. 2007. Including the effects of pressure management in calculations of short run economic leakage levels. Paper presented at the IWA International Specialised Conference, Water Loss 2007, September, 2007, in Bucharest. http://www.leakssuite.com/Documents/Papers/003_Fantozzi.pdf (accessed 29-Aug-08).

Farley, Malcolm. 2003. Understanding and managing losses in water distribution networks. Water & Wastewater International, September, 2003. http://www.pennnet.com/display_article/189881/20/ARTCL/none/none/1/Understanding-and-managing-losses-in-water-distribution-networks/ (accessed 3-Sep-08).

Fleming, K., J. Dugandzic, M. LeChevallier, and R. Gullick. 2006. Susceptibility of potable water distribution systems to negative pressure transients. The State of New Jersey - Division of Science, Research and Technology. <http://www.state.nj.us/dep/dsr/dw/susceptibility-potablewater.p65.pdf> (Accessed 29-Aug-08).

Fleming, Kala. 2007. Susceptibility of PWS to negative pressure transients. Presented at AWWA Research Committee Seminar, 22-Oct-07. http://www.vaawwa.org/files_PDFs/2007resrch_fleming.pdf (accessed 3-Sep-08).

Flowmetrix, Inc. Advanced water, gas, and petroleum leak detection digital systems and pipeline management. Maynard, MA: Flowmetrix, Inc. <http://www.flowmetrix.com/index.htm> (accessed 3-Sep-08).

Foundation for Cross-Connection Control and Hydraulic Research. 2002. Backflow introduction. Viterbi School of Engineering, University of Southern California. <http://www.usc.edu/dept/fccchr/introduction.html> (accessed 2-Sep-08).

Geldreich, E.E. 1996. Microbial Quality of Water Supply in Distribution Systems. Boca Raton, FL: Lewis Publishers.

Griffiths, Jeffrey K. 2008. Alternative secondary disinfectants: Advantages and Disadvantages. Vermont Water Supply Division, Department of Environmental Conservation. Disinfectant Byproduct Symposium, November, 2007, Vermont. www.vermontdrinkingwater.org/DBPsymposium/AlternativeSecondaryDisinfectants.ppt (accessed 2-Sep-08).

Grigg, N.S. 2004. Assessment and Renewal of Water Distribution Systems. AwwaRF Report Number 91025. Denver, CO.

Hammer, Mark J. and Hammer, Mark J., Jr., “Water and Wastewater Technology”, 5th edition (2003), Pearson-Prentice Hall

Harvie, Jamie, and Tom Lent. 2002. PVC-Free pipe purchasers’ report. Washington, DC: Healthy Building Network.
http://www.healthybuilding.net/pvc/pipes_report.html (accessed 2-Sep-08).

Haas, C.N. 1999a. Benefits of Using a Disinfectant Residual. Jour. AWWA 91(1):65-69.

Heneghan & Associates. 2004. Water loss - What is it? Civil Talk, September, 2004.
<http://www.haengr.com/Newsletters/newsletter92004.htm> (accessed 3-Sep-08).

Hetek Solutions, Inc. 2008. Water lost is water wasted – Working with the Water Loss Task Force. London, Ontario: Hetek Solutions, Inc.
http://www.hetek.com/index.php?option=com_content&task=view&id=22&Itemid=141 (accessed 3-Sep-08).

Higgins, M. S., P. O. Paulson. 2006. Fiber Optic Sensors for Acoustic Monitoring of PCCP, White Paper, Pure Technologies,
http://www.puretechnologiesltd.com/html/technical_papers.php?year=2006#link

Holmes, Matthew. 2005. Accounting for Total Water Use: A Water Loss Optimization Program. Albuquerque, NM: New Mexico Rural Water Association.
<http://nmcollaborations.nmt.edu/PDF%20Files/Accounting%20for%20Total%20Water%20a%20Water%20Loss%20Optimization%20Program%20Holmes%20Presentation.pdf> (accessed 3-Sep-08).

Hunaidi, Osama. 2000. Detecting leaks in water distribution pipes. National Research Council Canada , Construction Technology Update No. 40, Oct. 2000.
http://irc.nrc-cnrc.gc.ca/pubs/ctus/40_e.html (accessed 3-Sep-08).

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumia, and M.A. Maupin. 2004. Estimated Use of Water in the United States in 2000; US Geological Survey Circular 1268. Reston, Virginia: US Geological Survey.
<http://pubs.usgs.gov/circ/2004/circ1268/pdf/circular1268.pdf> (Accessed 26-Aug-08).

IDS Water. 2004. Leakage economics: Plugging the knowledge gap. Chicago, IL: IDS Publishing.
http://www.idswater.com/Common/exhib_64/WWT%20Leakage%20Economics%20Article%20Feb%202004.doc (accessed 3-Sep-08).

IDS Water. Trenchless pipe rehabilitation replacement, dynamic pipe bursting, pipe eating, static pipe bursting method, water flush drilling method. International Society for Trenchless Technology. Industry IDS, Inc.

http://www.idswater.com/water/us/ISTT/Trenchless_Pipe_Rehabilitation/10_0/g_supplier_4.html (accessed 2-Sep-08).

IWA Water Loss Task Force. 2007. Leak location and repair guidance notes. London, UK: IWA.
http://www.findmoreleaks.com/downloads/IWA%20LD%20Guidance%20Notes%20260307%20_2_.pdf (accessed 3-Sep-08).

IWA Water Loss Task Force. Water loss 2007. IWA Specialist Group, Efficient Operation and Management and Romanian Water Association. Specialist Conference, Bucharest, Romania, 23-26 September, 2007. <http://www.waterloss2007.com/> (accessed 3-Sep-08).

Jakubowski, Tom. 2006. Best management practices help control water loss. On Tap Magazine, Spring 2006, pp. 25-27. www.nesc.wvu.edu/pdf/DW/conserve/water_loss_otsp06.pdf (accessed 3-Sep-08).

Johnson, Randy. 2001. Drinking Water Contaminants. Drinking Water Resources website (Cyber-nook.com).
http://www.cyber-nook.com/water/tbl_cont.html (accessed 3-Sep-08).

Jones, G.M (Editor-in-Chief). 2006. Pumping station design, 3rd edition. Burlington, MA: Butterworth-Heinemann.

Karim, M. R., M. Abbaszadegan, and M. W. LeChevallier. 2003. Potential for Pathogen Intrusion during Pressure Transients. Jour AWWA 95(5):134-146.

Kenniwick, City of. 2004. Cross connection control: the key to safe, clean drinking water. City of Kennewick, WA.
http://www.ci.kennewick.wa.us/Municipal_Services/Cross_Connection_Control.asp (accessed 29-Aug-08).

Kidd, Benjamin. 2005. Disinfectant Residual Reporting. Presented at TCEQ Public Drinking Water Section, May 4, 2005. Texas Commission on Environmental Quality (TCEQ).
www.tceq.state.tx.us/files/TF2005_DLQOR.pdf 4319992.pdf (accessed 2-Sep-08).

Kingdom, B., R. Liemberger, and P. Marin. 2006. The challenge of reducing non-revenue water (NRW) in developing countries. Washington, DC: The World Bank.
<http://siteresources.worldbank.org/INTWSS/Resources/WSS8fin4.pdf> (Accessed 26-Aug-08).

Kirmeyer, G.J., W. Richards, and C.D. Smith. 1994. An assessment of water distribution systems and associated research needs. Denver, CO: AWWA Research Foundation: Distribution Systems.

Kiss, G., K. Koncz, and C. Melinte. 2006. WaterPipe project: an innovative high resolution Ground Penetration Imaging Radar (GPIR) for detecting water pipes and for detecting leaks and a Decision-Support-System (DSS) for the rehabilitation management of the water pipelines. Brussels: European Commission.
http://waterloss2007.com/pdf_vortraege/Mittwoch/A8-2.pdf (accessed 2-Sep-08).

Lahlou, Zacharia M. 2001. Leak detection and water loss control. Tech Brief, a National Drinking Water Clearinghouse Fact Sheet. The National Drinking Water Clearinghouse, National Environmental Services Center, West Virginia University.
http://www.nesc.wvu.edu/ndwc/pdf/OT/TB/TB_LeakDetection.pdf (accessed 3-Sep-08).

Lambert, Allan. 2003. What do we know about pressure:leakage relationships in distribution systems? Presented at the IWA Conference 'System approach to leakage control and water distribution systems management', May, 2000, in Brno, Czech Republic.

Leak-Pro Co. Water leak detection equipment and training with audio generator, leak-pro.com. Lake Montezuma, AZ: Leak-Pro.
<http://www.leak-pro.com/> (accessed 3-Sep-08).

Leakssuite.com. Concepts. Leakssuite Software, ILMSS Ltd.
<http://www.leakssuite.com/Documents/Concepts.html> (accessed 3-Sep-08).

LeChevallier M.W., R.W. Gullick, M.R. Karim, M. Friedman, J.E. Funk. 2003. The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. J Water Health 1(1):3-14.

Levin, Ronnie B., Paul R. Epstein, Tim E. Ford, Winston Harrington, Erik Olson, and Eric G. Reichard. 2002. US drinking water challenges in the twenty-first century. Environmental Health Perspectives 110 (Suppl. 1)February 2002.
<http://www.ehponline.org/members/2002/suppl-1/43-52levin/EHP110s1p43PDF.PDF> (accessed 3-Sep-08).

Liemberger, R., K. Brothers, A. Lambert, R. McKenzie, A. Rizzo, T. Waldron. Water loss performance indicators. Presented at the Water Loss 2007 Conference, 23-26 September 2007, in Bucharest, Romania.
http://waterloss2007.com/pdf_vortraege/Montag/B2-1.pdf (accessed 3-Sep-08).

Liemberger, Roland. 2002. Do you know how misleading the use of wrong performance indicators can be? Paper presented at the IWA Managing Leakage Conference, November, 2002, in Cyprus.
<http://www.bws-malaysia.com/common/nrw/download/papercyprus1.pdf> (accessed 29-Aug-08).

Liemberger, Roland. 2006. Introduction to water loss analysis and reduction. Presentation at the IWA World Water Congress and Exhibition, September, 2006, in Beijing, China.
http://www.liemberger.cc/diverse_uploads/Water%20Loss%20workshop%20presentation%201%20-%20Roland%20Liemberger.pdf (Accessed 28-Aug-08).

Longley, Alison. Asbestos in drinking water. Seattle, WA: Pacific Sciences Institute.
<http://www.mindspring.com/~sjccancer/ASBESTOS%20IN%20DRINKING%20WATER.htm> (accessed 2-Sep-08).

Makar, J.M., R. Desnoyers, and S.E. McDonald. 2000. Failure modes and mechanisms in gray cast iron pipe. Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario, Canada. Presented at Underground Infrastructure Research 2001 in Waterloo,

Ontario, June, 10-13. <http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc44218/nrcc44218.pdf> (accessed 2-Sep-08).

Marshallsay, Dene. 2007. Managing water loss at least cost: The economic level of leakage. Presented at Reducing Non-Revenue Water: Best Practices and Technologies, 2 October 2007, in Lisbon.

<http://www.epal.pt/epal/pdfs/EPALBritishWaterSeminarOct2007/11%20Dene%20Marshallsay%20WRc.pdf> (accessed 3-Sep-08).

Matichich, Mike. 2006. Making asset management real and accessible now. Presented during PNWS-AWWA Webcast, 9-Oct-06.

<http://www.pnws-awwa.org/Files/Introduction%20-%20Matichich%20CH2M%20HILL.pdf> (accessed 3-Sep-08).

Mays, Larry W. 1996. Water resources handbook. New York, NY: McGraw-Hill.

McNeill, Laurie S. 2000. Water quality factors influencing iron and lead corrosion in drinking water. Phd diss., Virginia Polytechnic Institute and State University. Digital Library & Archives, University Libraries, Virginia Tech.

<http://scholar.lib.vt.edu/theses/available/etd-07102000-12010045> (accessed 2-Sep-08).

MDE (Maryland Department of the Environment). 2003. Developing and implementing a water conservation plan. Baltimore, Maryland: Maryland Department of the Environment Water Supply Program.

http://www.mde.state.md.us/assets/document/water_cons/wcp_guidance2003.pdf (accessed 3-Sep-08).

Merritt, Frederick S., M. Kent Loftin, and Jonathan T. Ricketts. 1996. Standard handbook for civil engineers, 4th ed. New York, NY: McGraw-Hill.

Mills, Samuel, and Dwayne Rathburn. 2006. San Antonio water system 2005 stat book. SAWS (San Antonio Water System), Infrastructure Planning Department, San Antonio, Texas.

http://www.saws.org/our_water/aquifer/StatsBook/docs/2005_StatsBook.pdf (accessed 3-Sep-08).

Munich Re Group. 2004. Technology for underwriters 22: Locating leaks after water damage. München, Germany: Münchener Rückversicherungs-Gesellschaft.

http://www.munichre.com/publications/302-00878_en.pdf (accessed 3-Sep-08).

MUS (Morristown Utility Systems). 2007. Water rates. Morristown, TN: MUS.

http://www.morristownutilities.org/water_rates.html (accessed 3-Sep-08).

NACE (National Association of Corrosion Engineers). 2008. Cost of corrosion slide presentation. Houston, TX: NACE, International.

http://events.nace.org/publicaffairs/cost_corr_pres/cost_corrosion.ppt#281,31,Slide 31 (accessed 3-Sep-08).

Najafi, Mohammad, and Sanjiv B. Gokhale. 2004. Trenchless technology: Pipeline and utility design, construction, and renewal. New York, NY: McGraw-Hill Professional.

National drought Mitigation Center, Lincoln NE. <http://drought.unl.edu/dm/monitor.html> (accessed 5-Aug-08)

NDMC (National Drought Mitigation Center). 2006. Planning for drought. National Drought Mitigation Center, University of Nebraska, Lincoln.
<http://drought.unl.edu/plan/plan.htm> (accessed 2-Sep-08).

Neptune Technology Group. 2006. ARB® Utility Management Systems™ for water utilities. Tallahassee, AL: Neptune Technology Group, Inc.
<http://www.neptunetg.com/uploadedFiles/BuildSystem.pdf> (accessed 3-Sep-08).

New York Leak Detection, Inc. Water & gas leak detection, ground penetrating radar, pipe & cable locating, pipeline testing, video inspections, fire flow testing, mapping. Jamesville, NY: NYLD, Inc.
<http://wefindleaks.com/?src=overture> (accessed 3-Sep-08).

NRC (National Research Council). 2005. Public water supply distribution systems: Assessing and reducing risks - First report. Washington, DC: The National Academies Press.

NRC-CNRC (National Research Council of Canada). 2008. Water mains: the importance of inventory and failure data. Construction Innovation 13(1), March 2008.
http://irc.nrc-cnrc.gc.ca/pubs/ci/v13no1/v13no1_6_e.html (accessed 3-Sep-08).

NUS Consulting Group. 2008. 2007-2008 International water report & cost survey. New York/London/Paris/Düsseldorf/Milan/Johannesburg/Stockholm/Brussels/Sydney/Toronto/Madrid: National Utility Service, Inc.
<http://www.nusconsulting.com/downloads/2008WaterAbridged.pdf> (Accessed 26-Aug-08).

O'Brien, Les, et al. 1986. Buster Backflow. Joe Sinardi, art and layout. Gainesville, FL: Gainesville Regional Utilities. <http://www.abpa.org/Doc/PDF/Buster%201%20Sample.pdf> (Accessed 29-Aug-08).

O'Brien, Les. 2006. Your drinking water. TREEO Center, University of Florida.
<http://www.mindspring.com/~loben/water.htm> (accessed 2-Sep-08).

O'Day, D.K., R. Weiss, S. Chiavari, and D. Blair. 1986. Water Main Evaluation for Rehabilitation/Replacement. Denver, CO: AWWA Research Foundation and Environmental Protection Agency.

Ofwat (The Water Services Regulation Authority). 2005. Economic level of leakage. Birmingham, England, UK: Ofwat.
[http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/disclog_260805.pdf/\\$FILE/disclog_260805.pdf](http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/disclog_260805.pdf/$FILE/disclog_260805.pdf) (accessed 3-Sep-08).

Ofwat (The Water Services Regulation Authority). 2007. International comparison of water and sewerage service 2007 report. Birmingham, England, UK: Ofwat.
[http://www.ofwat.gov.uk/publish.nsf/AttachmentsByTitle/int_comparison2007.pdf/\\$FILE/int_comparison2007.pdf](http://www.ofwat.gov.uk/publish.nsf/AttachmentsByTitle/int_comparison2007.pdf/$FILE/int_comparison2007.pdf) (accessed 3-Sep-08).

OPS (Ontario Provincial Standards for Roads and Public Works). 2005. Construction specifications for cement mortar lining of water mains. Ontario provincial standard specification OPSS 462, November, 2005. Waterloo, Ontario, Canada: University of Waterloo, Department of Civil Engineering.
<http://www.civil.uwaterloo.ca/catt/Pdfs/OPSS462Nov05.pdf> (accessed 3-Sep-08).

Oxford Plastics, Inc. 2008. Polyethylene Pipe - A Brief History of Poly Pipe. Ontario, Canada: Oxford Plastics, Inc.
<http://www.oxfordplasticsinc.com/polyethylene.htm> (accessed 2-Sep-08).

Parrott, Ralph W., H. Loyd Thornton. 2003. Proprietary tracer gas hydro-test leak detection system saves time, money. Pipeline & Gas Journal, March, 2003.
http://findarticles.com/p/articles/mi_m3251/is_3_230/ai_n25064998 (accessed 2-Sep-08).

Pearson, D. and S W Trow. 2005. Calculating Economic Levels of Leakage. From Leakage 2005 - Conference Proceedings.
<http://waterloss2007.com/Leakage2005.com/pdf/Calculating%20Economic%20Levels%20of%20Leakage.pdf> (accessed 3-Sep-08).

Pilcher, R., S. Hamilton, H. Chapman, D. Field, B. Ristovski, and S. Stapely. 2007. IWA leak location and repair guidance notes. IWA Specialist Group, Efficient Operation and Management, Water Loss Task Force.
http://www.leakageforum.org/index.php?option=com_docman&task=doc_details&gid=71&Itemid=33 (accessed 3-Sep-08).

Plastics Pipe Institute. Smooth-wall High-Density Polyethylene pipe systems, 9M 4/2000 PP. Washington, DC: Plastics Pipe Institute.
www.plasticpipe.org/pdf/high_density_polyethylene_pipe_systems.pdf (accessed 2-Sep-08).

PolyPipe, Inc. 2007. Polyethylene pipe - Municipal water pipe. Gainesville, TX: PolyPipe, Inc.
<http://www.polypipeinc.com/municipalwater.asp> (accessed 3-Sep-08).

PPFA (Plastic Pipe and Fittings Association). CPVC products - frequently asked questions. Glen Ellyn, Illinois: Plastic Pipe and Fittings Association.
<http://www.ppfahome.org/cpvc/faqcpvc.html> (2-Sep-08).

Propex Services, LLC. Polybutylene piping. Asheville, NC: Propex Services, LLC.
http://www.propex.com/C_f_env_polybu.htm (accessed 3-Sep-08).

Propex. 2005. Polybutylene piping, plumbing - Environmental hazard. Asheville, NC: Propex Services, LLC.
http://www.propex.com/C_f_env_polybu.htm (2-Sep-08).

QDNR (Queensland Department of Natural Resources). 2000. Improving water use efficiency in Queensland's urban communities. Brisbane, Queensland: QDNR.
http://www.nrw.qld.gov.au/compliance/wic/pdf/reports/urban_wateruse/07_leakage_red.pdf (accessed 3-Sep-08).

Rajani, B., and S. McDonald. 1994. Water mains break data on different pipe materials for 1992 and 1993. Ontario, Canada: NRC-CNRC (National Research Council of Canada).
http://www.ipexinc.com/Content/EN_CA/4_0_Thermo_Today/4_3_Economie/Water_Mains_Break (accessed 3-Sep-08).

Reiber, Steve. 2005. The changing face of distribution system management. Water & Wastes Digest 45(12), December 2005.
<http://www.waterinfocenter.com/The-Changing-Face-of-Distribution-System-Management-article6558> (accessed 3-Sep-08).

Repipe News. What you need to know about polybutylene plumbing. Herndon, VA: Repipenews.com.
<http://www.repipenews.com> (accessed 2-Sep-08).

Robeyns, J. and P. Vanspeybroeck. 2005. Molecular oriented PVC (MOPVC) and PVC-U pipes for pressure applications in the water industry. Plastics, Rubber and Composites 34(7):318-323.
<http://www.pvc4pipes.org/documents/files/PXII/sess4b/Vanspeybroeck.pdf> (accessed 2-Sep-08).

Rowett Research Institute. Body composition. Rowett Institute of Nutrition and Health, The University of Aberdeen.
http://www.rowett.ac.uk/edu_web/sec_pup/body_comp.pdf (accessed 2-Sep-08).

Selvakumar, A., Clark, R.M., and Sivaganesan, M. 2002. Cost for water supply distribution system rehabilitation. USEPA, EPA/600/JA-02/406.
<http://www.epa.gov/nrmrl/pubs/600ja02406/600ja02406.pdf> (accessed 3-Sep-08).

Sensus Metering Systems. Potable water meter test kits, SM-767. Sensus North American AMI.
<http://na.sensus.com/Module/Catalog/File/water?id=226> (accessed 2-Sep-08).

Sigma Hellas, Limited. 2005. Correlators. Piraeus, Greece: Sigma Hellas, Ltd.
http://www.sigmahellas.gr/sectors/water_wastewater/Special_equipment/special_categories/correlators.htm (accessed 3-Sep-08).

Sjøvold, Frøydis, SINTEF; Peter Mobbs, WRc; SGI. 2005. TILDE- Tools for Integrated Leak Detection - D20 Benchmarking Tools. EC Contract No. IPS-2001-42077 TILDE. Brussels: European Commission.
<http://www.waterportal.com/comunication/document/D20Benchmarkingtools.pdf> (Accessed 28-Aug-08).

Stephens, Ian. 2002. Economic levels of leakage. Presented at the International Conference on Water Loss Reduction and Control Programs in Water Supply Systems, 2-3 December 2002.
[http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/is_021202.ppt/\\$FILE/is_021202.ppt.ppt](http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/is_021202.ppt/$FILE/is_021202.ppt.ppt) (accessed 3-Sep-08).

Stratus Consulting. 1998. Infrastructure Needs for the Public Water Supply Sector. Report for American Water Works Association. Boulder, CO. December.

Strosser, P., J. Roussard, B. Grandmougin, M. Kossida, I. Kyriazopoulou, J. Berbel, S. Kolberg, J.A. Rodriguez-Diaz, P. Montesinos, J. Joyce, T. Dworak, M. Berglund, C. Laaser. 2007. EU water saving potential (Part 2 – case studies) Institute for International and European Environmental Policy, ENV.D.2/ETU/2007/0001r, July 19, 2007.
http://ec.europa.eu/environment/water/quantity/pdf/water_saving_2.pdf (accessed 3-Sep-08).

SubSurface Leak Detection, Inc. 2006. LC-2500 leak noise correlator. San Jose, California: SubSurface Leak Detection, Inc.
http://www.subsurfaceleak.com/lc2500_prod_pg.html (accessed 3-Sep-08).

Sutter County, California. 2008. Section 6: Domestic water supply system. In Sutter County design standards document. Sutter County Water Resources Division.
http://www.co.sutter.ca.us/pdf/pw/design_standards/DS9_Section_6_Water_Supply.pdf (accessed 3-Sep-08).

Tangram Technology Ltd. 2004. PVC-u or PVC-U? What's in a name? Hitchin, Herts, UK: Tangram Technology Ltd. <http://www.tangram.co.uk/TI-PVC-U.html> (accessed 2-Sep-08).

Tangram Technology Ltd. 2008. Polymer names. Hitchin, Herts, UK: Tangram Technology Ltd. <http://www.tangram.co.uk/TI-Polymer-Names.html> (accessed 2-Sep-08).

Tatro, Margie. 2004. A systems view of the nation's energy future. Albuquerque, NM: Sandia National Laboratories.
www.steab.org/docs/handout_alba_2004_11_tatro.ppt (accessed 20-Aug-08).

Tatro, Margie. 2007. Realizing North America's energy security for the future. Albuquerque, NM: Sandia National Laboratories.
<http://northamericaninstitute.org/files/symposia/tatro-energy-ppt.pdf> (accessed 21-Aug-08).

The Engineering Toolbox. 2005. Leakage Classifications of Control Valves. Engineeringtoolbox.com.
http://www.engineeringtoolbox.com/control-valves-leakage-d_484.html (2-Sep-08).

Thornton International Ltd. 2005. Metropolitan Nashville Water Services (MWS) water audit and leakage management projects, USA 2003 to 2009. Sao Paulo, Brazil: Thornton International Ltd. <http://www.water-audit.com/WorldProjects.htm#Nashville> (accessed 2-Sep-08).

Thornton, J., R. Sturm, G. Kunkel. 2008. Water loss control, 2nd edition. New York, NY: McGraw-Hill.

Trevelyan, J., and H.P. Hack. 1994. Analysis of stray current corrosion problems using the boundary element method. In *Boundary element technology IX*, C A Brebbia and A J Kassab, eds., pp. 348-356. Southampton; Boston: Computational Mechanics Publications.

Tullmin, M. 2007. Water loss. Water pages (Corrosion-club.com). Tullmin Consulting.
<http://www.corrosion-club.com/waterfigures.htm> (accessed 3-Sep-08).

Turner Designs. Rhodamine WT and fluorescent tracer dye application notes; Fluorescent tracer studies. Turner Designs, Inc.
http://www.turnerdesigns.com/t2/doc/appnotes/tracer_dye.html (2-Sep-08).

TWDB (Texas Water Development Board) and Mark Mathis. 2005. Water Loss Manual. Austin, Texas: Texas Water Development Board.
http://www.twdb.state.tx.us/assistance/conservation/Municipal/Water_Audit/Leak_Detection/WaterLossManual_2005.pdf (accessed 29-Aug-08).

Twedt, Steve. 2002. A sea of drinking water lost between treatment, tap. Pittsburgh Post-Gazette website (Post-gazette.com), July 15, 2002, Health & Science, Environment Section.
<http://www.post-gazette.com/healthscience/20020715water0715p1.asp> (accessed 3-Sep-08)

Twedt, Steve. 2002. The water system can be taken for granted, until it goes bad close to home. Pittsburgh Post-Gazette website (Post-gazette.com), July 15, 2002, Health & Science, Environment Section.
<http://www.post-gazette.com/healthscience/20020715breaks0715p3.asp> (accessed 3-Sep-08).

US Army. 1986. Technical Manual TM 5-813-5/AFM 88-10, Vol. 5, Water supply, water distribution. US Army and US Air Force Joint Departments.
http://www.army.mil/usapa/eng/DR_pubs/dr_a/pdf/tm5_813_5.pdf (Accessed 29-Aug-08).

US Army. 1992. Water supply: Pumping stations, Technical Manual No. 5-813-6. Washington, DC: Headquarters, Department of the Army.
http://www.wbdg.org/ccb/ARCHIVES/ARMYCOE/COETM/tm_5_813_9.pdf (accessed 2-Sep-08).

US Army Corps of Engineers (USACE), 2001. Washington, D.C., CEMP-R, Public Works Technical Bulletin 420-49-36 – Leak Detection”,
http://www.wbdg.org/ccb/ARMYCOE/PWTB/pwtb_420_49_36.pdf , (accessed 2-Sep-08).

UKSTT (United Kingdom Society for Trenchless Technology). 2005. Lining techniques. Warwickshire, UK: UKSTT.
http://www.ukstt.org.uk/trenchless_technology/lining_techniques/ (accessed 3-Sep-08).

United Nations Environment Programme, Global Environment Outlook (2000) Chapter 2, Regional Synthesis <http://www.unep.org/geo2000/english/index.htm>

USEPA (US Environmental Protection Agency). 2002. Cases in water conservation. Office of Water (4204M), EPA/832-B-02-003.
http://www.epa.gov/watersense/docs/utilityconservation_508.pdf (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2002. Community water system survey (2000) Vol. 1. Office of Water (4607M) EPA/815-R-02-005A, December 2002".
http://www.epa.gov/ogwdw/consumer/pdf/cwss_2000_volume_i.pdf (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2002. Deteriorating buried infrastructure management challenges and strategies. Office of Water (4601M), Office of Ground Water and Drinking Water, Distribution System Issue Paper.
http://www.epa.gov/safewater/disinfection/tcr/pdfs/whitepaper_tcr_infrastructure.pdf (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2003. Small drinking water systems handbook. Water Supply and Water Resources Division (WSWRD), National Risk Management Research Laboratory, Office of Research & Development, EPA/600/R-03/041 May 2003.
www.epa.gov/nrmrl/pubs/600r03041/600r03041.pdf (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2005. Drinking water infrastructure needs survey and assessment. Office of Water (4606) EPA/816-R-05-001.
http://www.epa.gov/safewater/needssurvey/pdfs/2003/report_needssurvey_2003.pdf (Accessed 29-Aug-08).

USEPA (US Environmental Protection Agency). 2005. Water distribution system analysis: Field studies, modeling and management. Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division, EPA/600/R-06/028. <http://www.epa.gov/nrmrl/pubs/600r06028/600r06028.pdf> (Accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2006. Distribution system indicators of drinking water quality. Office of Water (4601M) Office of Ground Water and Drinking Water Total Coliform Rule Issue Paper, December, 2006.
http://www.epa.gov/safewater/disinfection/tcr/pdfs/issuepaper_tcr_indicators.pdf (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2007. Aging water infrastructure research program: Addressing the problem through innovation. Office of Research and Development, National Risk Management Research Laboratory, EPA/600/F-07/015.
<http://www.epa.gov/ORD/NRMRL/pubs/600f07015/600f07015.pdf> (Accessed 29-Aug-08).

US Census Bureau <http://www.census.gov/main/www/cen2000.html> accessed August 2008

USEPA (US Environmental Protection Agency). 2007. Distribution system inventory, integrity and water quality. Office of Ground Water and Drinking Water.
http://www.epa.gov/OGWDW/disinfection/tcr/pdfs/issuepaper_tcr_ds-inventory.pdf (Accessed 27-Aug-08).

USEPA (US Environmental Protection Agency). 2007. Small drinking water systems: State of the industry and treatment technologies to meet the safe drinking water act requirements. Water Supply and Water Resources Division, National Risk Management Research Laboratory, EPA/600/R-07/110, September 2007.
<http://www.epa.gov/nrmrl/pubs/600r07110/600r07110.pdf> (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2008. Small public water systems and capacity development. EPA.gov website, Water, Ground Water & Drinking Water, Small Public

Water Systems Section.

<http://www.epa.gov/safewater/smallsystems/managementhelp.html> (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2008. Sustainable infrastructure for water & wastewater. EPA.gov website, Energy and Water Section.

http://www.epa.gov/waterinfrastructure/bettermanagement_energy.html (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). 2008. Water quality in small community distribution systems. Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division, EPA/600/R-08/039.

<http://www.epa.gov/nrmrl/pubs/600r08039/600r08039.pdf> (Accessed 29-Aug-08).

USEPA (US Environmental Protection Agency). Decision-support tools for predicting the performance of water distribution and wastewater collection systems. National Risk Management Research Laboratory, Office of Research and Development EPA/600/R-02/029.

<http://www.epa.gov/nrmrl/pubs/600r02029/600R02029.pdf> (accessed 3-Sep-08).

USEPA (US Environmental Protection Agency). Drinking water data & databases. Water, Ground Water and Drinking Water Section.

<http://www.epa.gov/safewater/databases/index.html> (accessed 3-Sep-08).

Velan, Inc. 2003. Valve leakage. Williston, VT: Velan Field Engineering Services.

<http://www.valvediagnostics.com/leakage/index.htm> (accessed 2-Sep-08).

Vinindex Systems & Solutions. Supermain PVC-O. Reece Australia Limited.

http://www.reece.com.au/new/pdf/products/Supermain_PVC-O.pdf?civil (accessed 2-Sep-08).

WQHC (The Water Quality & Health Council). 2008. Safe water delivered safely.

Waterandhealth.org.

<http://www.waterandhealth.org/drinkingwater/safewater.html> (accessed 3-Sep-08).

WRRRC (Water Resources Research Center). 1994. Leaks Plague Polybutylene Plumbing. Water Resources Research Center, the University of Arizona.

<http://ag.arizona.edu/AZWATER/awr/nov94/leaks.html> (accessed 2-Sep-08).

WSSC (Washington Suburban Sanitary Commission). WSSC water meter tests (5/8" - 1½" Meters). Laurel, Maryland: WSSC.

<http://www.wssc.dst.md.us/service/MeterTesting.cfm> (accessed 3-Sep-08).

Yu, Myong-jin, Mi-jeong Jang, Sanghyuck Park, Byoung-kwon Park, and Ja-yong Koo. 2007. Application of CIPP (cured in place pipe) for water pipe rehabilitation. Dept. of Environmental Engineering, University of Seoul, Korea. Paper presented at the ROMA07 Mediterranean NODIG XXV International Conference & Exhibition, October 10-12, 2007.

http://www.iattmed.com/pdf/s3_11_Myong.pdf (accessed 2-Sep-08).

Zhao, J.Q. 2003. Slipline rehabilitation of water mains with high-density polyethylene pipe. *Construction Technology Update* No. 56, Jan. 2003.

http://irc.nrc-cnrc.gc.ca/pubs/ctus/56_e.html (accessed 29-Aug-08).

Cook, Jack S. 2008. Mapping water losses – A success story. V1 Magazine (Vector1media.com), Articles Section. <http://www.vector1media.com/article/column/mapping-water-losses-%96-a-success-story/> (accessed 4-Sep-08).

Wu, Zheng Yi, and Paul Sage. 2006. Water loss detection via genetic algorithm optimization-based model calibration. Presented at the ASCE 8th Annual International Symposium on Water Distribution System Analysis, August 27-30, 2006, in Cincinnati, OH. www.genetic-programming.org/hc2006/Wu-Paper-2.pdf (accessed 4-Sep-08).

MDE (Maryland Department of the Environment). 2003. Water supply program water audit guidance. Maryland Department of the Environment, Water Supply Program. www.mde.state.md.us/assets/document/water_cons/Water_Audit_guidance.pdf (accessed 4-Sep-08).

PSC (Public Service Commission of Wisconsin). 2006. Water – The Wisconsin numbers. Madison, Wisconsin: PSC. www.psc.wi.gov/utilityinfo/water/newsinfo/document/waterWiNumbers2005.pdf (accessed 4-Sep-08).